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ELECTRONIC POWER SUPPLIES

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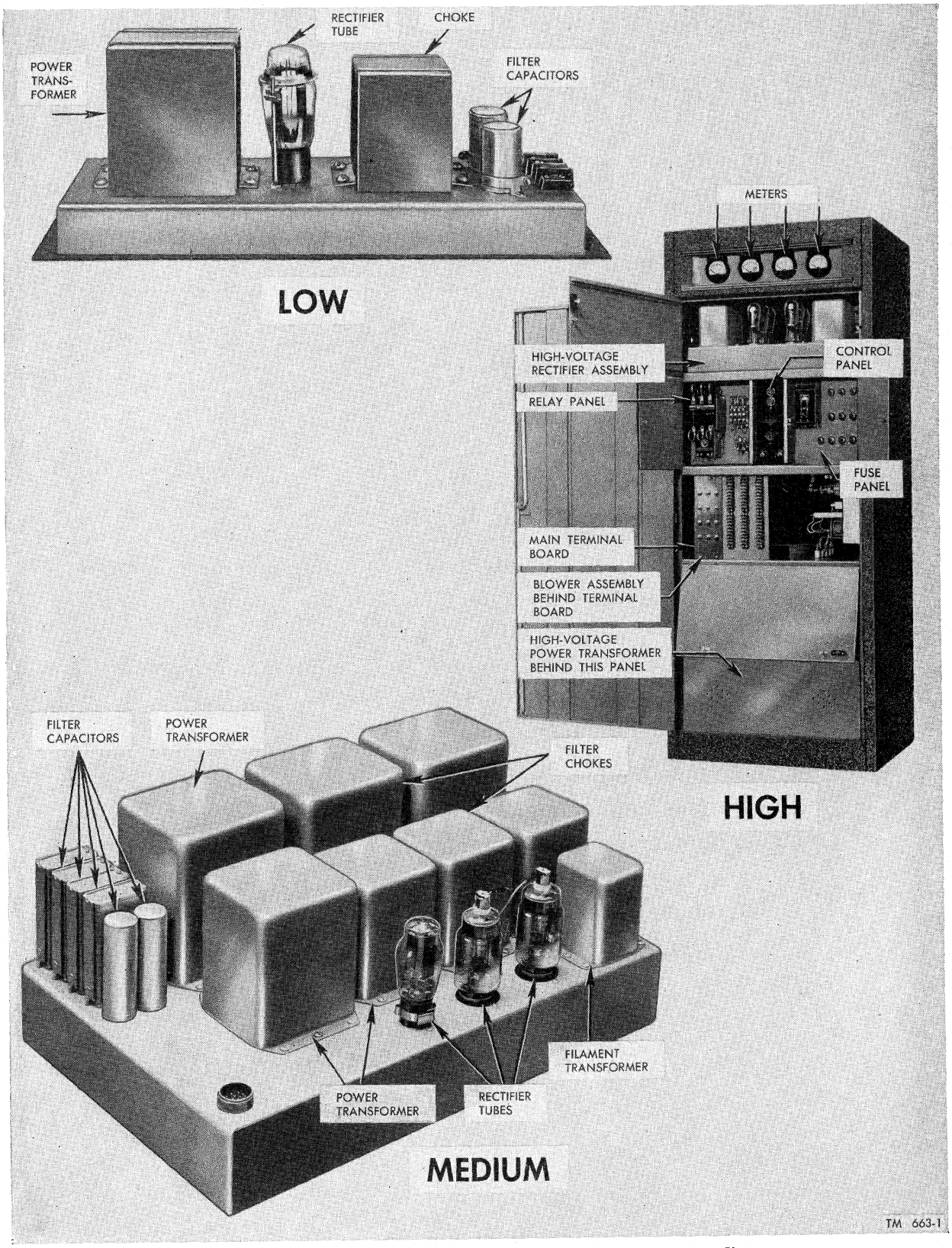

Figure 1. Examples of low-, medium-, and high-voltage power supplies.

CHAPTER 1

INTRODUCTION

1. Need for Power Supply

Sources of electrical power are required for the operation of all electronic communications equipment used by the armed services. These sources can be batteries or generators, which are considered prime power sources, or they can be devices which convert the outputs of prime sources into electrical forms required by particular pieces of equipment. These conversion devices commonly are known as *power supplies.*

2. Function of Power Supply

The function of the power supply and some prime power sources is to provide the correct operating voltages and currents for the electron-tube circuits, relays, d-c (direct-current) motors, and other components found in communications equipment. Although a-c (alternating current) can be used for many heater and filament circuits, the power supply must provide direct current, as pure as possible, and of the proper value to fulfill the voltage requirements of the plates, screens, and grids of the electron tubes. Usually, this is accomplished by rectifying and filtering the applied a-c voltages. Pure direct current is required for receiving equipment to prevent objectionable hum from interfering with the signal in the output. In transmitters, pure d-c is required to prevent modulation of the carrier frequency by power-supply hum.

3. Terminology

The power used to heat the filaments of vacuum tubes often is called the A supply and normally is of low voltage. Plate and screen power units are called B supplies. Bias voltages for control-grid circuits are called C supplies. The terminology originated in the days when radio sets were powered exclusively by batteries, known as **A, B,** or C batteries according to the particular circuit in which they functioned.

4. Voltage and Current Requirements

Voltage and current requirements vary widely, from the relatively low values used in receivers to the high values required for transmitters and radar sets. The larger equipments use several power supplies, each fulfilling the needs of particular circuits. The high-voltage B source is sometimes a separate unit and uses large components to withstand the stress of the high potentials and the heavy plate current it must furnish for the proper operation of transmitter tubes. Heater and filament current requirements have a wide range, from milliamperes for small tubes to hundreds of amperes needed to operate large tubes. Each power supply must be designed to fulfill the voltage and current requirements of the specific equipment.

5. Types of Primary Power Sources (fig. 1)

Primary power sources can be divided into three general classes—batteries, commercial a-c and d-c power lines, and electromechanical systems (table I).

a. Battery Sources. The use of dry cells in military communications equipment is limited to small hand-held and other portable units. Because of low-current output and short life, the battery is not suitable for use as a *primary source* for power supplies. However, the storage batteries in vehicles are satisfactory for this application. The relatively low d-c voltages are converted to high d-c voltages by dynamotors or vibrator power supplies. Filament or heater circuits of electron tubes, control relays, and motors usually operate directly off the batteries.

Table I. Types of power supplies

Available prime power source	Type of power supply required	Nature of output voltage	Usual application
Battery (vehicular storage)	Vibrator Dynamotor	D-c, any voltage level	A, B, and C supply for mobile communication equipment.
	High-vacuum diode-rectifier.	D-c, any voltage level	B and C supply for stationary communication equipment. Radar equipment. Medical electronic equipment. Other devices.
Commercial power lines: D-c from 115 to 220 volts. A-c from 115 to 440 volts, single or polyphase 25, 40, 50, 60 cps.	Mercury-vapor rectifier	D-c, high voltage	Stationary communication equipment of relatively high power. Radar equipment.
	Dry-disk or metallic rectifiers.	D-c, lower voltage levels	Battery chargers, A, B, and C supplies for light portable communication equipment.
	Gas-tube rectifier	D-c, low-voltage levels	Applications requiring low-voltage high-current supply. Battery chargers.
Electromechanical	Same types as for commercial power lines.	Same as for commercial power lines.	Same as for commercial power lines; more particularly for semiportable field equipment.

b. Commercial Power Systems. Various values of a-c and d-c voltages can be obtained from commercial power lines and used as primary power sources. The a-c voltage ranges from the standard 115-volt, single-phase power source to 2,300-volt, three-phase power used for industrial purposes. The primary d-c voltage source ranges from 32 to 440 volts. Commercial a-c voltage is available in frequencies of 25, 40, 50, and 60 cps (cycles per second), 60 cps being the most widely used. Communication power supplies designed for operation on 115-volt, 60-cps lines can be connected directly to these lines. Power supplies designed for a-c operation must not be connected to a d-c source, or the power transformer will be damaged. Conversely, equipment designed exclusively for a d-c source will not operate on a-c power. Equipment designed for both a-c and d-c operation will work equally well on either, if polarity is observed on the d-c source. When the primary source is a-c the phase of the line voltage must be considered. Single-phase equipment can be connected to the common lead plus one other lead of a polyphase line, but polyphase equipment can be connected only to lines that provide a polyphase voltage of the proper value. Transformers can be used to step up or down the a-c voltages. See table I for types of power supplies operated from commercial lines.

c. Electromechanical Systems. Electromechanical rotating systems are used widely because they permit generation of electrical power on the spot where portable or transportable electronic equipment is operated. Electromechanical power equipment includes motor generators, gasoline-engine-driven generators, hand-driven generators, rotary converters, inverters, and dynamotor systems. The last three systems are driven electrically. The prime power source drives the mechanical system, which turns a generator, and the output of the generator provides the desired form of power. The vibrator can be included under inverter systems as a nonrotating means of generating a-c using a d-c prime power source.

6. Input Voltages

a. D-C Input Voltages. D-c input voltages can be obtained from any of the three primary voltage sources described previously and range in value from a few volts to several hundred volts. Power supplies designed for operation on commercial d-c lines differ considerably from those designed for a-c operation and are not used extensively. Direct current as obtained from a battery source, being pure d-c, requires no rectifying or filtering and therefore can be applied directly to battery-operated equipment. D-c voltages obtained from power-line or electromechanical

sources carry small fluctuations known as *ripple* which must be smoothed out before the voltage can be used.

b. A-C Input Voltages. With the exception of vehicular storage-battery units, a few power supplies designed to operate from commercial d-c sources, and a limited number for combined a-c/d-c operation, power supplies used by the armed services operate with a-c input. Because of its flexibility and the ease with which it can be stepped up or down to higher or lower values the use of a-c is widespread. Voltages from as low as a few volts to many thousands of volts can be obtained from transformers operated on 115–volt lines. The factor that determines these voltages is the step-up or step-down turns ratio of the transformer windings. Communications equipment, radar sets, and various other electronic equipments require very high voltages which can be obtained conveniently from a-c input sources.

c. Single-Phase Voltages. Single-phase voltages are generated when the coils on the armature of an a-c generator are connected in series to form a single winding. The open ends of the rotating armature winding are brought out and connected to slip rings. The output of this generator is a single-voltage waveform alternating at a predetermined frequency (A, fig. 2). Single-phase power commonly is found in residential areas.

d. Two-Phase Voltages. Two-phase voltages are generated when the coils on the armature are displaced 90 electrical degrees from each other (B, fig. 2). The output from such a system consists of two voltage waveforms, one starting from 0 when the other has passed through 90°. This system is used in the operation of large motors and other power devices. Two separate single-phase circuits can be obtained from a two-phase source.

e. Three-Phase Voltages. An improvement over the two-phase system of power generation is the 3-phase system (C, fig. 2), which has wide industrial application. The armature coils in a 3-phase generator are displaced 120° *electrically*. The output voltage waveform consists of three

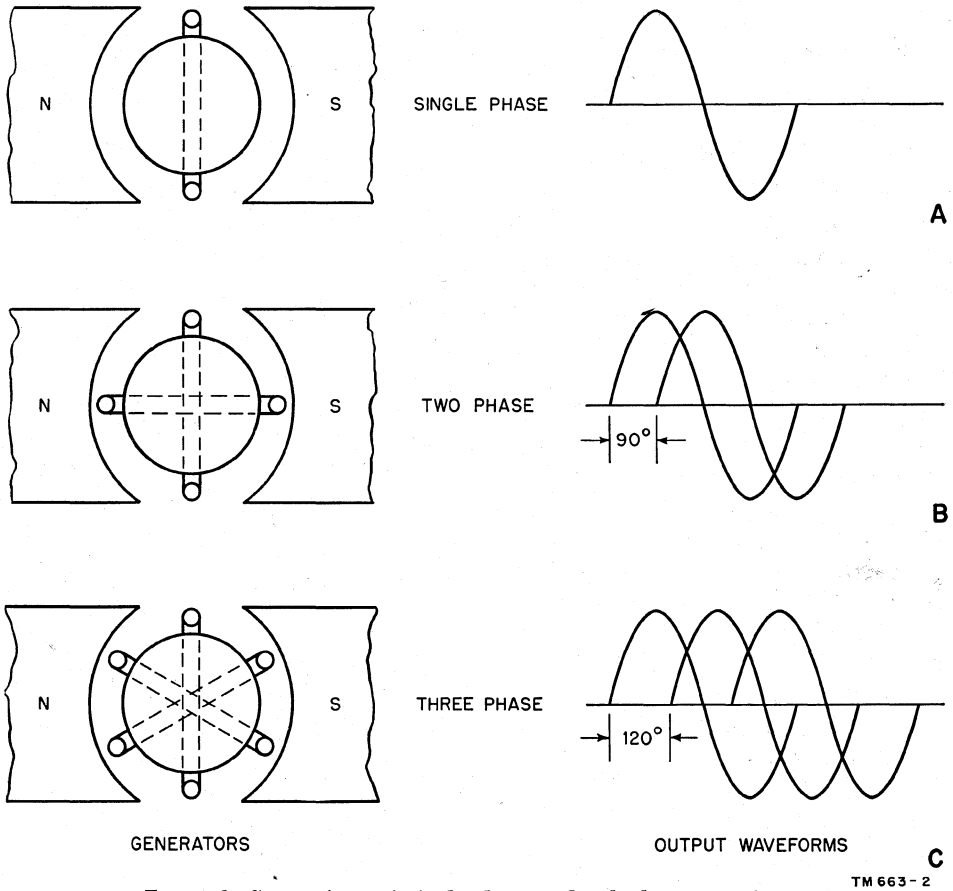

Figure 2. Comparison of single-phase and polyphase waveforms.

waves, each starting from 0 when the preceding wave has passed through 120°. Most industrial power is derived from 3-phase systems because of their high efficiency and flexibility. Polyphase systems find extensive application in radar sets, large transmitting and receiving equipments, and other power-consuming electronic devices used by the Armed Forces. The output voltages from power supplies with polyphase input voltages are easier to filter, and provide a much higher average value of output voltage than is obtainable from single-phase systems.

f. Batteries. When a battery is used as a primary source of input voltage, it must be able to deliver sufficient power to take care of the voltage and current requirements of the power supply. Therefore, it must be capable of delivering a high current since the filament voltages of a power supply require low voltage and high current. The vehicular battery is a wet-cell or storage battery and can deliver the high current needed. Since it is used in tanks, trucks, and airplanes and is usually 6, 12, or 24 volts depending on the type of vehicle, it can serve as a primary source of power. Dry cells generally are not capable of delivering a high amount of current and seldom are used as a primary source of power.

7. Frequencies of Input Voltages

a. Range of Frequencies. A-c voltages are generated at various frequencies throughout the world. These frequencies have been grouped into two general categories by the electrical industry: 25 to 40 cps and 50 to 60 cps. Equipment designed for use in the 50- to 60-cps group is not suitable for use on 25- to 40-cps power systems. However, equipment intended for 25- to 40-cps use will operate satisfactorily on the higher frequency systems, provided that it fulfills the output voltage requirements. Some equipment is designed for universal application and can be used efficiently on any of these line frequencies. Frequencies of 400 to 1,000 (or more) cps are used in certain communications equipment supply by local generating apparatus and have the advantage of requiring smaller and lighter component parts. Equipment designed for these frequencies, however, cannot be used on 25- to 40- or the 50- to 60-cps power lines.

b. Frequency Applications. In the application of the various power line frequencies, certain advantages and disadvantages exist in each of the two general categories. In the 25- to 40-cps group, the voltage drop per unit current and length of line is less and the voltage regulation on transmission lines is better. Certain motors and synchronous converters function better at the lower frequencies. These low frequencies introduce a pronounced flicker, however, which makes their use objectionable for lighting purposes. The 50- to 60-cps group introduces no objectionable flicker in electric lamps and is suitable for both light and power. In addition, transformers designed for these frequencies are much lighter and less costly than those operating on the lower frequencies. These factors account for the widespread use of the 50- to 60-cps group of line frequencies.

c. Frequency Shift and Power-Supply Output. Since the frequency of an alternating current and the value of the delivered a-c voltage are functions of the speed of rotation of the generator rotor, any variation in frequency is accompanied immediately by a change in the value of the delivered voltage. If the rpm (revolutions-per-minute) of the rotor become less than the rated value, the frequency and available a-c voltage fall in value; any increase in the rotor speed causes increased frequency and voltage output. If sufficiently great, these variations in input voltage have an adverse effect upon the power-supply output. Actually, only a small change in frequency occurs in commercial power lines because of the rigid control systems used to maintain the rated speed of the generator. An example of this rigid control of frequency is in the operation of electric clocks. The accuracy of the clock depends on a nonvarying frequency, and, in many power systems, the frequency is held so close to the standard that the daily variation in the time of electric clocks is not more than a few seconds. However, in locally operated generating systems not having efficient controls, the frequency shift can be substantial if not closely watched and corrected. The low primary voltage accompanying a falling off in frequency can reduce the output of the power supply to the point where the efficiency of the communications equipment might be impaired. On the other hand, the application of higher than rated input voltage, indicated by a rise in the frequency, might cause a breakdown or power-supply components.

d. Frequency Limitations. The limit of frequency shift that can be tolerated depends on the type of equipment and the amount of voltage regulation incorporated in the power source. Usually, a deviation of not more than one-half cycle from standard is the maximum permissible shift, and the power frequency should be held as closely as possible within this limit.

8. Power-Supply Components

Basically, an a-c power-supply system consists of a power transformer, a rectifier, filter capacitors, filter chokes, and a bleeder resistor or voltage-divider system (fig. 3). Where constant voltage

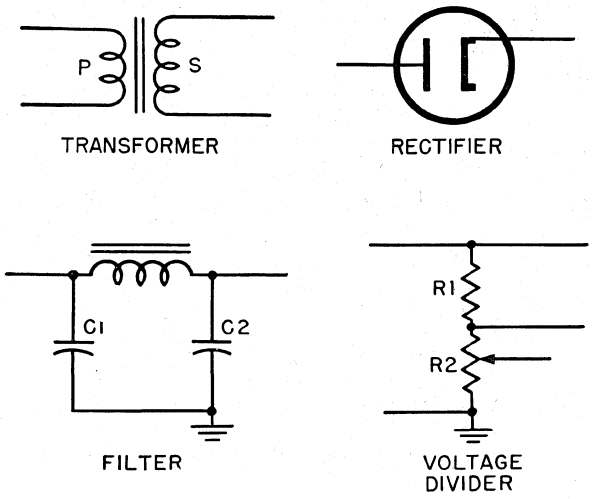

Figure 3. Graphic symbols of power-supply components.

is required, a regulator tube or some other regulating device is incorporated in the circuit. Filament power for the tubes can be provided from a winding on the power transformer, or from separate filament transformers, depending on the total power required and the arrangement of the particular circuit being supplied.

a. Power Transformers (fig. 4).

(1) The purpose of the power transformer is to increase or decrease the a-c input voltage to the values required by the rectifiers and filaments of the equipment in use. Usually, the transformer consists of a primary winding, a high-voltage secondary winding, and a number of low-voltage windings to supply power for rectifier-tube filaments and the filaments of other tubes in the communication equipment. A great variety of transformers is available commercially, some containing several high-voltage secondaries to supply different rectifiers, plus a number of filament windings. The term *high voltage* is used here in a relative sense to distinguish this winding from other windings that can provide low voltages for filaments or other purposes. The high voltage supplied by the secondary winding depends on the particular power-supply requirements. Power transformers are rated according to the voltage and line frequency of the a-c source, and the output voltages and power required by the secondary loads, and are designed accordingly.

(2) Because of the large a-c currents that the transformer must handle, overheating is more of a problem in power transformers than it is in other types of transformers. Excessive heating causes a breakdown in the insulation between the windings, and consequently a power transformer failure. The large a-c current circulating in the transformer induce voltages at many points and even though they are small, they set up additional currents known as *eddy currents*. These eddy currents serve no useful purpose but they do generate heat and cause power loss. To reduce this heat the transformer core is laminated. Heating also can be reduced by mounting the transformer so that there is free circulation of air around its surfaces. Rectifier transformers used in high-power circuits sometimes are incased in oil to provide the required cooling.

(3) The direct current flowing in the transformer secondary can cause saturation of of the transformer core. This reduces the number of magnetic flux lines and decreases the efficiency of the transformer. To prevent magnetic core saturation, an air gap of a few hundredths of an inch is placed in the core in the path of the magnetic flux.

(4) Electrostatic shielding is an important factor in the design of rectifier trans-

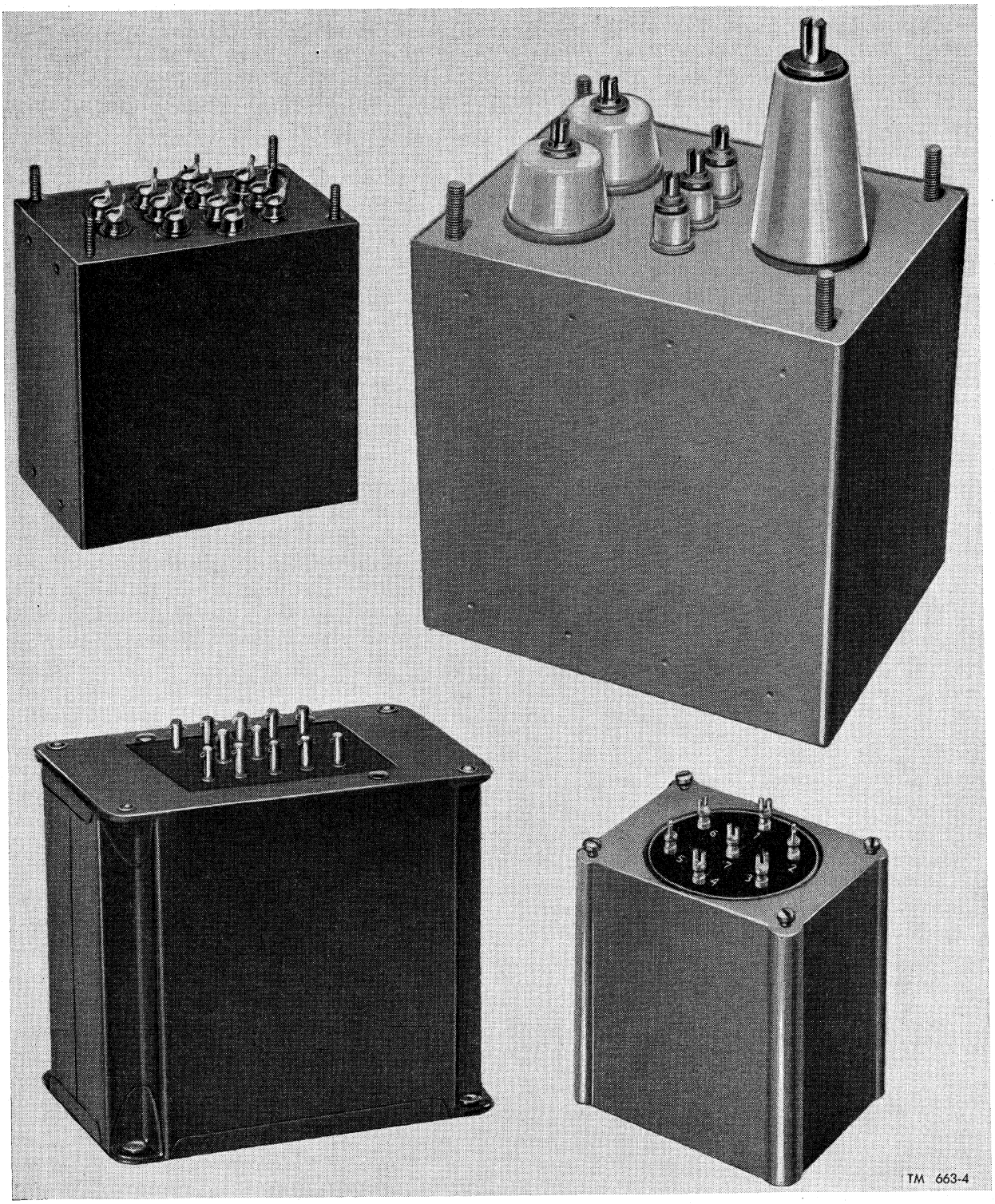

Figure 4. Representative types of power transformers.

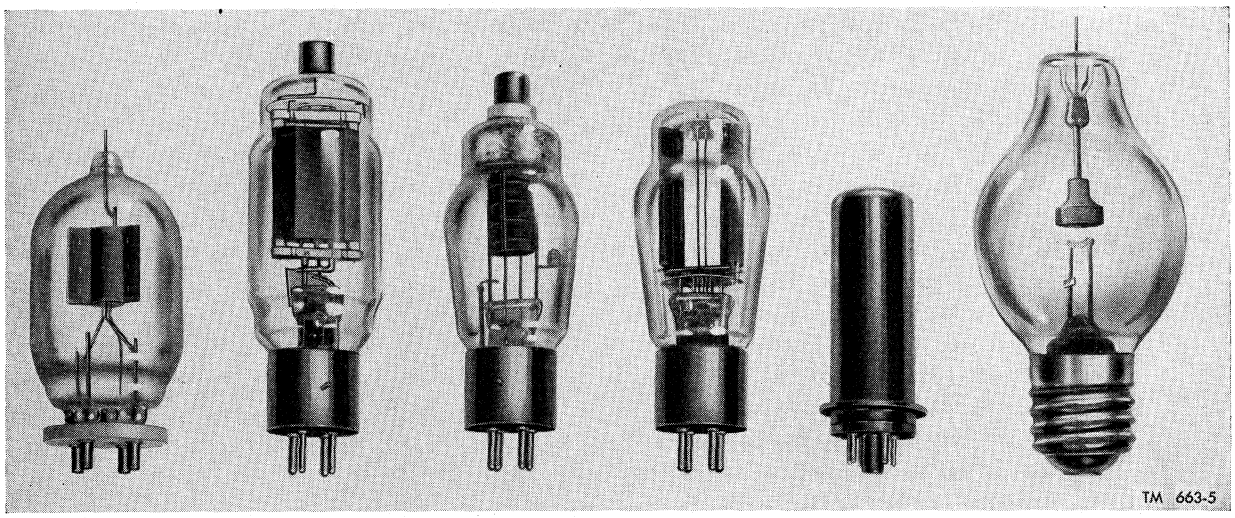

Figure 5. Various types of rectifier tubes.

formers. The shield usually is between the primary and the secondaries of the transformer, is bonded to the transformer case, and is connected to the chassis ground. The function of the electrostatic shield is to prevent high-frequency disturbances in the power line from being fed into the power supply and spurious oscillations from the communications equipment from being fed back into the power line.

b. Rectifiers

(1) The rectifiers used in power supplies can be of either the electron-tube or the metallic type. Their purpose is to rectify the a-c voltage applied to them from the transformer or a-c line into a unidirectional or pulsating d-c voltage. Different types of electron-tube and metallic rectifiers are available, each having its specific application. The rectifier is rated individually according to its voltage- and current-carrying capacities. All rectifiers, however, have the ability to pass current freely in one direction while limiting the flow of current in the opposite direction. Different types of rectifier tubes are shown in figure 5; metallic rectifiers are illustrated in figures 17 and 20.

(2) Rectifiers used in power supplies can be classified as follows:

Electron-tube rectifiers		Metallic rectifiers
Ignition	High-vacuum	Copper-oxide
Tungar	Mercury-vapor	Copper-sulphide
Cold-cathode	Mercury-arc	Selenium

c. Filter Capacitors (fig. 6).

(1) *General.* Filter capacitors used in power-supply circuits can be divided into the following basic categories: electrolytic, paper, mica, and ceramic. The purpose of the capacitor is to aid in filtering the pulsating direct current delivered by the rectifier. The filter capacitor used depends on the design of the power supply and the value of voltage required at the output. Each category can be separated into a number of types to fit any specific application.

(2) *Electrolytic capacitors.* Dry electrolytics are inclosed in cardboard containers impregnated with wax. Wire leads are brought out from the capacitor plates for connection to the external circuit. The dry electrolytic capacitor finds limited military application, because the electrolyte, not being hermetically sealed, dries out, and the value of capacitance changes with changes in temperature and humidity. The wet electrolytic capacitor is inclosed in a metal can and, usually, is hermetically sealed against the ef-

fects of temperature and humidity. This capacitor is used widely in military communication equipment. In general, electrolytic capacitors cannot be used on voltages above 500, and proper polarity must be observed when connecting them into the circuit.

(3) *Paper capacitors.* Paper capacitors can be wax-impregnated, or they can be filled or impregnated with oil. Wax-impregnated capacitors are constructed in cardboard or metal containers and have limited applications for military use. Oil-filled or oil-impregnated paper capacitors, furnished in hermetically sealed cans, are most widely used.

(4) *Mica capacitors.* Mica capacitors are used in power-supply circuits requiring low-capacitance units operating at high voltages. These capacitors provide stable filtering action and are used extensively in the power supplies of cathode-ray tubes.

(5) *Ceramic capacitors.* Ceramic capacitors are used as trimmer, bypass, and high-voltage filter capacitors. Some trimmer and bypass ceramic capacitors are constructed to compensate for changes in capacitance caused by an increase in temperature; these are called *temperature-compensating capacitors.* At present, high-voltage filter capacitors usually are not temperature-compensating. Ceramic capacitors are used widely in the high-voltage supplies for cathode-ray tubes; special capacitors are available for use in transmitters and high-frequency power circuits.

d. Chokes (fig. 7). Filter chokes are used in conjunction with filter capacitors to further the filtering action of the pulsating voltage delivered from the rectifier. Chokes are rated according to their resistance, inductance, and current-carrying capacity. They vary in size from the small chokes used in receiver power supplies to the large units in radar and transmitting equipments.

e. Bleeders and Voltage Dividers. The high-voltage surges occurring in the power supply when the unit first is turned on are limited by the resistor across the output of the power supply. A certain amount of output voltage regulation is obtained in this manner. This resistor also serves to *bleed* off the charge on the filter capacitors when the power supply is turned off. For this reason, the resistor (or a series of resistors) is called a *bleeder.* Often, a number of different values of voltage must be provided from one power supply for the operation of different circuits. This can be accomplished readily by tapping the required

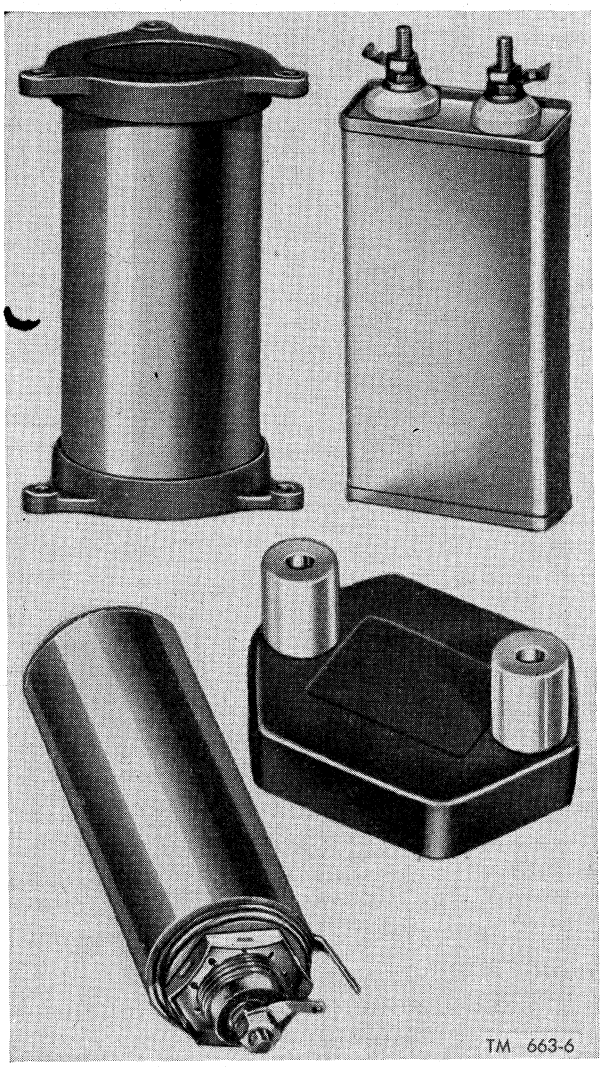

Figure 6. Various types of filter capacitors used in power supplies.

voltages from appropriate points along the bleeder. Since the tapped resistor divides the total voltage from the output of the power supply into the correct values required by the different circuits (fig. 8) it is called a *voltage divider.* The wattage rating of the voltage divider must be sufficient to carry both the bleeder current and the current required by the devices connected to

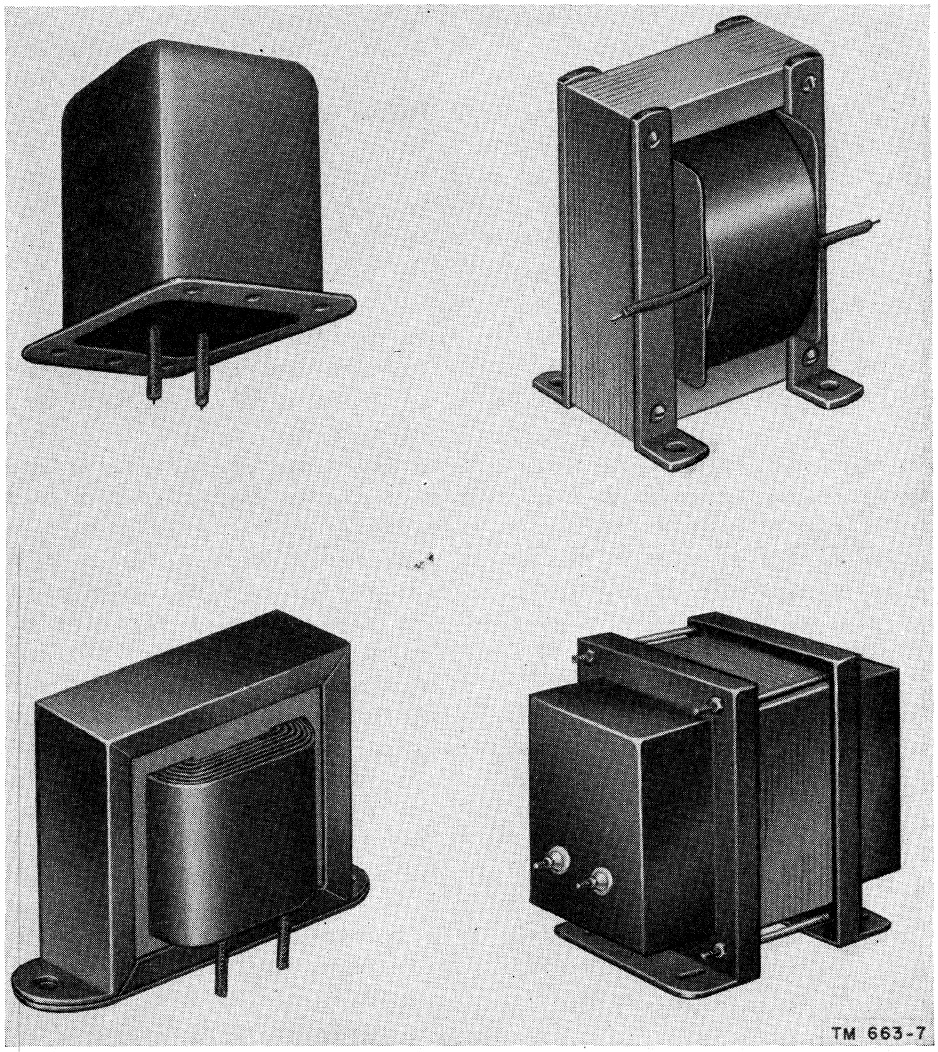

Figure 7. Different types of filter chokes used in power supplies.

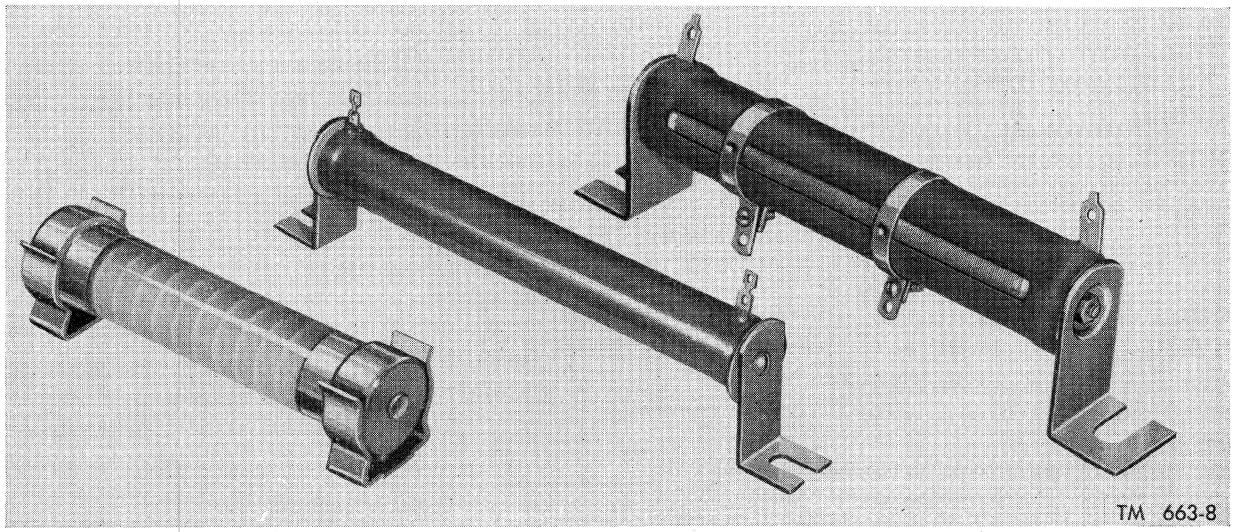

Figure 8. Different types of resistors used as bleeders and voltage dividers in power-supply circuits.

the output of the power supply. Voltage dividers are covered in greater detail in chapter 5.

f. Voltage Regulators. When the output voltage from the power supply must be maintained at a constant value despite input voltage or load variations, some additional means other than the bleeder resistor must be provided. To give this control, certain devices known as *voltage regulators* are connected into the power-supply circuit. These are designed in various forms, but are usually tube types for plug-in operation. In some cases, the tube is a ballast resistor, or a gas-filled glow-discharge tube, such as a neon tube. Regular electron tubes also may be used in special circuit arrangements to provide the required regulation, and, sometimes, a combination of electron-tube and glow-tube regulation is used. Another regulator used is a specially designed transformer in which magnetic saturation of the core provides the required regulation. Regardless of the device used, the action is basically the same—that of providing a constant value of output voltage from the power supply irrespective of reasonable variations in input voltage or load current. This is discussed in detail in chapter 6.

9. Practical Circuit Arrangements

Although many variations exist in their design, power supplies can be broken down into three basic classifications—low-voltage, medium-voltage, and high-voltage.

a. Low-Voltage Power Supplies (fig. 9). Power supplies ranging in output voltage from

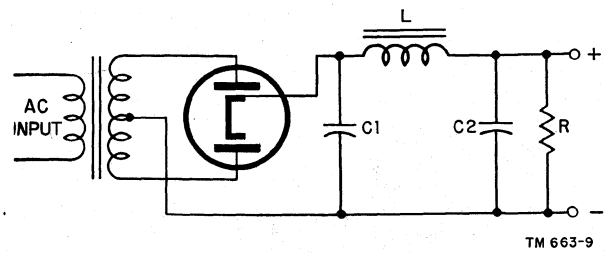

Figure 9. Simple low-voltage power-supply circuit.

about 6 volts to approximately 500 volts and several hundred milliamperes of current are considered low-voltage power supplies. Low-voltage power supplies used in radio receivers and small transmitters, and the low-voltage circuits of oscilloscopes and similar equipment have output voltages ranging up to approximately 500 volts. Any of the common rectifiers, such as electron tubes (high-vacuum or gaseous) and metallic units, can be used at these operating voltages.

b. Medium-Voltage Power Supplies. A medium-voltage power supply is one in which the output voltage ranges from a lower limit of about 500 volts to an upper limit of 1,200 or 1,500 volts. Actually, no distinct line of demarcation exists in establishing whether a voltage should be classified low, medium, or high. The classifications given here are in general use and are applicable for practical service.

c. High-Voltage Power Supplies. High-voltage power supplies are rated from 1,000 volts upward. They are essentially the same in circuit arrangement as the low-voltage types. For operation with standard 117-volt input voltages, however, special power transformers with a large turns ratio are required to step up the voltage to the required values. The components in this supply are large and heavily constructed, with a high degree of safety factor. Rectifiers can be connected in various circuit arrangements to utilize the full value of voltage existing across the transformer secondary. A simple power-supply circuit operating off the power lines and designed to supply a cathode-ray tube is shown in figure 10. Here a resistor is used instead of a choke in the filter section. In this application, the resistor provides sufficient filtering action. Another method of developing high voltages is by means of an r-f pulse occurring across a specially designed r-f transformer. The output of the transformer is connected to a rectifier tube designed for this purpose and is rectified in the conventional manner. This type of power supply is used widely in television equipment.

d. Bias-Voltage Supplies. In addition to supplying voltages of various values which are positive with relation to B minus or ground, power supplies also can furnish control-grid voltages for amplifier stages which are negative with relation to their individual cathodes. Since the polarity of the voltage that appears across any resistor can be determined simply by remembering that electrons always flow from negative to positive, the negative voltages required can be developed by moving the ground or reference point to different taps along the voltage divider (fig. 11). In order to interpret voltage measurements in the power supply correctly, it is necessary to understand this discussion concerning polarity and zero-reference

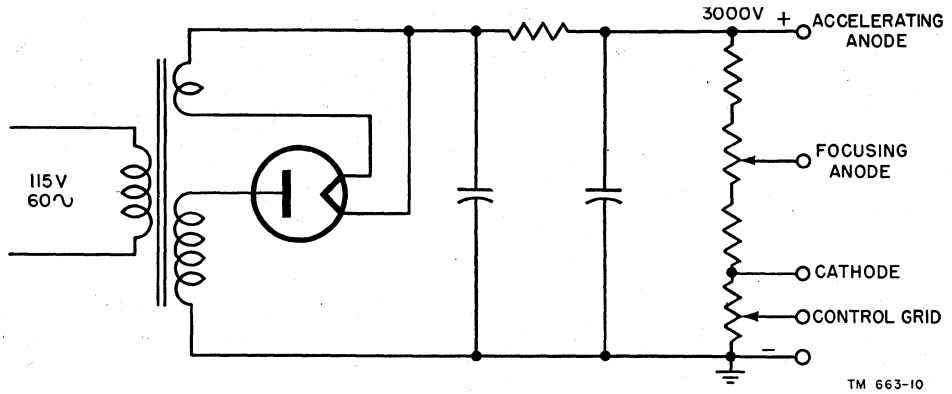

Figure 10. Simple high-voltage power-supply circuit.

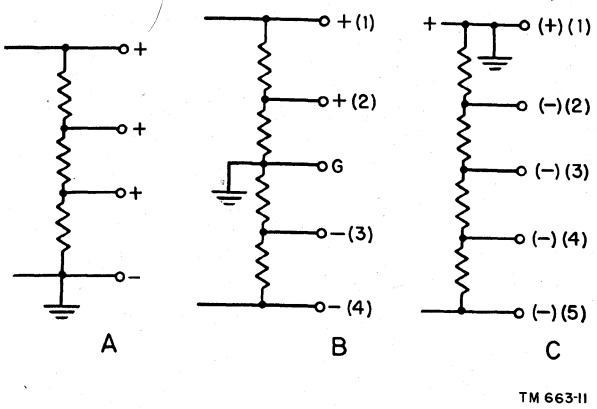

Figure 11. Bias voltages and zero-reference points.

points. In A, the low end of the voltage divider is grounded. With this arrangement, all the voltages tapped off the voltage divider are positive in polarity with relation to ground, and the maximum voltage exists between ground and the high end of the voltage divider. When the ground point or reference level is moved to the tap G, as in B, the voltages in the upper half of the divider will be positive with relation to ground and the voltages in the lower half will be negative with relation to ground. Note that the maximum voltage still will be across the whole voltage divider; the only thing changed in the circuit is the reference point and the polarity of the voltages with relation to the reference point. In C, the ground point or reference level has been moved to the top of the voltage divider; all the voltages will be negative with relation to the ground point, and the maximum voltage still will be across the whole voltage divider. Since the maximum voltage is always across the whole voltage divider, and since the polarity of the voltages with relation to the ground or reference point can be varied, the voltage divider can be used to regulate the value and polarity of the voltages available at the output of the power supply.

e. Unregulated and Regulated Power Supplies.

(1) Although limited variations in the value of output voltage can be tolerated in some power supplies, others require that the voltage be maintained at a specific value. The first type of supply is known as an unregulated supply; the second type uses some form of regulation and is called a regulated power supply. As explained previously (par. 8*e*), the bleeder resistor or voltage divider affords some regulation of the output voltage, but this is not sufficient to hold the output voltage values to a close tolerance, and for all practical purposes this circuit is unregulated. The variations existing in the output are the result of changes in the load being supplied with power, or of variations occurring in the applied input voltage. Commercial power lines near large cities usually are held by automatic regulation to plus or minus 10 percent of the rated line voltage, and these variations do not affect appreciably the efficiency of the power supply. Small communities do not have the same degree of regulation and the line voltage can vary considerably. This condition applies, also, to local generating plants used in conjunction with military equipment where considerable variation in voltage can occur unless precautions are taken to prevent it.

(2) In an unregulated power supply, any change in the load connected to the supply produces an immediate change in the power-supply output voltage. Additional current drain by the load causes a drop in the available output voltage. The current drawn by the load cannot be held constant under all conditions of equipment operation and wide variations in current drain may occur in accordance with the operational requirements of the load. Even with these wide variations of current drain, a constant voltage might still be required for efficient operation. Since low-operating voltages greatly reduce the efficiency of the operating equipment, and since this can be tolerated rarely in military applications, regulated power supplies are a must in most cases. This subject is treated in greater detail in chapter 6.

10. Summary

a. Power-supply systems are required to provide correct operating potentials for electronic communications equipment.

b. The design and physical size of the power supply depend on the voltage and current requirements of the particular equipment supplied.

c. The three primary power sources are batteries, commercial power lines, and local electromechanical systems.

d. Power-line frequencies have been grouped into two general categories, 25 to 40 cps and 50 to 60 cps.

e. The most commonly used line frequency in North America is 60 cps.

f. The basic components in a power supply are power transformer, rectifier, filter capacitors, filter chokes, and voltage divider.

g. A rectifier is a device that permits a ready flow of current in one direction but cuts off or limits the current flow in the opposite direction.

h. Rectified current always is pulsating in nature and must be filtered for most applications.

i. The purpose of the filter capacitors and chokes in a power-supply system is to smooth out the pulsations existing in the rectified current.

j. A voltage divider is a resistor connected across the output of the power-supply system and tapped at specific points to provide the varied operating potentials required by communication equipment.

k. In order to insure a constant value of output voltage despite variations in either the input voltage or the output current drawn by the load, some form of voltage regulation must be provided in the power supply.

11. Review Questions

a. What is the function of a power supply?

b. Name the basic primary power sources.

c. What constitutes an electromechanical system?

d. What are the power-line frequency standards in the United States?

e. What is the effect of changing frequency on the output voltage?

f. What are the basic components in a power-supply system?

g. Describe a rectifier.

h. Name the different types of filter capacitors.

i. What is the purpose of the voltage divider?

j. What is a voltage regulator?

k. What is meant by a low-voltage power supply?

l. How can negative bias voltages be obtained from the power-supply system?

CHAPTER 2

SINGLE-PHASE RECTIFIERS

Section I. GENERAL

12. Purpose of Various Types of Rectifiers

a. The function of a rectifier is to change alternating current into direct current. Any device that permits current to flow only when the anode is positive with relation to the cathode may be used as a rectifier. The output of a rectifier is not pure direct current, but pulsating direct current, that can be smoothed out by proper filtering. The two most common rectifiers in use are the electron-tube (diode) and the metallic or dry-disk rectifier. The electron-tube rectifier can be divided into two classifications: the high-vacuum thermionic tube and the gaseous tube. Table II is a listing of some of the more commonly used rectifier tubes, showing operating characteristics. The selenium rectifier is the most frequently used metallic rectifier.

b. Electron-tube rectifiers are rated according to alternating voltage per plate, peak inverse voltage, load current, and peak plate current. The alternating voltage per plate is the highest amount of rms (root-mean-square) voltage that can be applied between the cathode and the plate of the rectifier tube, and the open-circuit voltage of the transformer or power source should not exceed this value. The peak inverse voltage represents the maximum negative voltage that can be applied to the plate of the tube with relation to its cathode when the tube is not conducting. Under normal operating conditions this voltage is equal to the maximum voltage of the transformer secondary, although *transients* may cause a considerably higher voltage. The peak plate current is determined by the cathode structure of the tube and represents the maximum emission that can be expected from the cathode or filament during the normal life of the tube. The load current is the peak current that the rectifier can safely deliver to the load.

13. Advantages and Disadvantages

a. The high-vacuum thermionic rectifier tube generally is a diode, and it is used widely in the development of both low and high d-c voltages. The tube can be used as a diode (half-wave rectifier), with only one alternation of the a-c input rectified, or as a double diode (full-wave rectifier) which rectifies both alternations of the voltage cycle. The high-vacuum rectifier is used where a small or moderate amount of current must be supplied. A characteristic of this rectifier is the high internal voltage drop, which limits its use where large values of current and voltage are required by the load. In this case, the increased internal voltage drop caused by the high current becomes excessive.

b. Of the gaseous rectifier tubes, the one used most extensively is the mercury-vapor tube. This tube is a diode into which a small amount of ionizing gas, or mercury vapor, has been injected. When operating potentials are applied to the tube, electrons flow from the cathode to the plate in the conventional manner. In passing through the space between the two elements, however, they collide with the atoms of mercury vapor and a process called ionization occurs. The impact of the electron colliding with the mercury-vapor atom knocks one or more electrons free and leaves the atom a positive ion. These free electrons join the stream flowing to the plate, and increase the current flow through the tube. The positive ions created by the bombardment of the gas atoms are attracted to the negative cathode where they neutralize the space-charge effect which tends to restrict the current flow. The result of this is a decrease in the internal resistance of the tube and a further increase in the current flowing through it. In its ionized state, the internal voltage drop in the tube

assumes a steady value of 10 to 15 volts regardless of the value of current drawn from the supply. Consequently, the over-all efficiency of the mercury-vapor tube is much higher than that of the high-vacuum tube. Mercury-vapor tubes usually have oxide-coated cathodes with a high thermionic efficiency, and both heater and filament cathodes are used. This rectifier tube is used in high-voltage circuits where a large amount of current must be supplied.

c. When the operating temperature of a mercury-vapor rectifier falls below a certain point, the amount of ionization decreases, causing the internal voltage drop to rise to excessive values with attendant destruction of the cathode. High operating temperatures cause *flashback* (conduction in the inverse direction) at much lower than rated inverse voltages. The plate voltage must not be applied until the cathode has been brought to an operating temperature sufficient to produce ionization. If these conditions are not satisfied, the high internal resistance (caused by the lack of ionization) produces a voltage drop of such magnitude that the cathode structure breaks down and the tube is damaged permanently. In addition to these disadvantages, the mercury-vapor rectifier tube requires special precautions, such as well-designed regulation and overload devices that automatically open the circuit when the current exceeds a predetermined value. These devices prevent damage from momentary overloads.

d. Cold-cathode rectifiers also are considered as gaseous rectifying devices, since they contain gas or mixtures of gases. Their application as power-supply rectifiers is extremely limited. These tubes are used mainly as voltage regulators, relaxation oscillators, switching, and surge protection devices and, therefore, are not discussed at length here.

e. Two metallic rectifiers that find wide application are the copper-oxide and the selenium rectifier, the latter being used more extensively. The copper-oxide rectifier generally is used in electrical measuring instruments because the uniformity of its output helps to insure the accuracy of the instruments. Copper-oxide rectifiers are used in low-voltage applications, because of a low in-

Table II. Characteristics of typical rectifier tubes

Type number	Rating			Filament data			
	Maximum allowable peak plate current amperes	Maximum inverse peak voltage	Average plate current amperes	Surge current amperes, maximum 0.1 sec.	Volts	Amperes	Type
HIGH-VACUUM TYPES							
5W4 [1]	0. 3	1, 400	0. 1		5	2	Oxide-coated.
5U4–G [1]	. 675	1, 550	. 225		5	3	Oxide-coated.
1V2	. 01	7, 500	. 0005		. 625	. 3	Oxide-coated.
1616	. 8	5, 500	. 13	2. 5	2. 5	5	Oxide-coated.
1B3–GT/8016	. 117	30, 000	. 002		1. 25	. 2	Oxide-coated.
Machlett Labs ML–1 [2]	. 3	140, 000	. 05		10	11. 5	Tungsten.
MERCURY-VAPOR TYPES							
83 [1]	1	1, 550	0. 225		5	3	Oxide-coated.
866/866–A	1	10, 000	. 25		2. 5	5	Oxide-coated.
869–B	10	10, 000	2. 5	100	5	18	Oxide-coated.
857–B	40	10, 000	10		5	30	Oxide-coated.
870–A [3]	450	16, 000	75	4, 500	5	65	Coated-cathode.
GAS-FILLED TYPES							
3B25	2	4, 500	0. 5	20	2. 5	5	Oxide-coated.

[1] These tubes have 2 filaments and 2 plates, and are, therefore, 2 half-wave rectifiers in a single envelope. Plate rating is for a single plate, whereas filament data are for both filaments.

[2] Must be operated oil-immersed.

[3] Must be operated with forced air cooling.

verse-voltage characteristic. Large amounts of current can be provided by both of these rectifying devices, the selenium rectifier being the more efficient.

14. Practical Applications

In practical applications, the high-vacuum electron-tube rectifier is found in a-m (amplitude-modulated) and f-m (frequency-modulated) radio receivers, in audio amplifiers, intercommunication systems, certain sections of transmitting equipment, radar sets, and in practically any electronic application where low or high voltages are required at a moderate value of current (table II). Mercury-vapor rectifiers are used where high-voltage and high current are required, as in radio and radar transmitters, high-voltage keying units, and similar equipment. Metallic rectifiers are used to operate small d-c motors and relays, to charge storage batteries, and to supply bias voltages for electron-tube circuits.

Section II. HALF-WAVE RECTIFIER

15. Circuit Arrangement

The basic circuits of two half-wave rectifiers are shown in A and B, figure 12. The two tubes differ only in the electron emitter, one being a filament or directly heated cathode, the other an indirectly heated cathode. The power transformers shown are typical and are designed to meet maximum voltage and current requirements. Any half-wave rectifying device, either a tube or a metallic rectifier unit, can be used in this circuit. Full-wave devices can be used in a half-wave circuit if the two rectifying sections are connected in parallel—that is, plate-to-plate and cathode-to-cathode when a full-wave rectifier tube is used (C and D, fig. 12). The half-wave rectifier can be described as a single rectifying unit in series with the applied a-c voltage and a load which is represented here by the reisitor R.

16. Half-Wave Rectifying Action

In A, figure 12, 2 cycles of input line voltage are shown above the primary of the transformer. By transformer action, these 2 cycles appear across the high-voltage secondary winding in reverse polarity and of a value determined by the turns ratio of the transformer. The voltage developed across the upper winding is used only to operate the filament of the tube. An examination of the waveforms existing across the transformer secondary shows that the first half-cycle of the stepped-up voltage is negative in polarity. This makes plate P of the diode negative with relation to its filament, and no current flows through the tube. During the following alternation, which is shown shaded, a voltage that is positive with relation to the cathode is applied to plate P. Since the positive charge on the plate attracts the electrons emitted by the filament, a pulse of current will flow through the circuit in the direction indicated by the arrows. On the next alternation, a negative voltage again is applied to plate P; this negative voltage on the plate will repel the electrons emitted by the filament or cathode, and no current will flow in the circuit. As long as input voltage is applied to the circuit, the tube will conduct on alternate halves of the cycle. Since current will flow only when the plate is positive with relation to the cathode, only one-half of the input voltage is rectified. Consequently, the name *half-wave* rectifier is given to the circuit.

17. Output Waveform

The half-wave rectifying action described above is demonstrated in the output waveform shown over the resistor, R (A, fig. 12). The shaded part of the output waveform is similar to the shaded part of the waveform applied to the diode plate P and corresponds to the positive half-cycle of the input voltage when a pulse of current passes through the circuit. The dotted alternations indicate the time interval when the diode is not conducting.

18. Peak and Average Values of Output Voltage

a. The output efficiency of the half-wave rectifier is low since only a half-cycle of the applied a-c voltage is utilized. The average value of the d-c voltage appearing at the output of the rectifier tube with a resistive load never can be more than

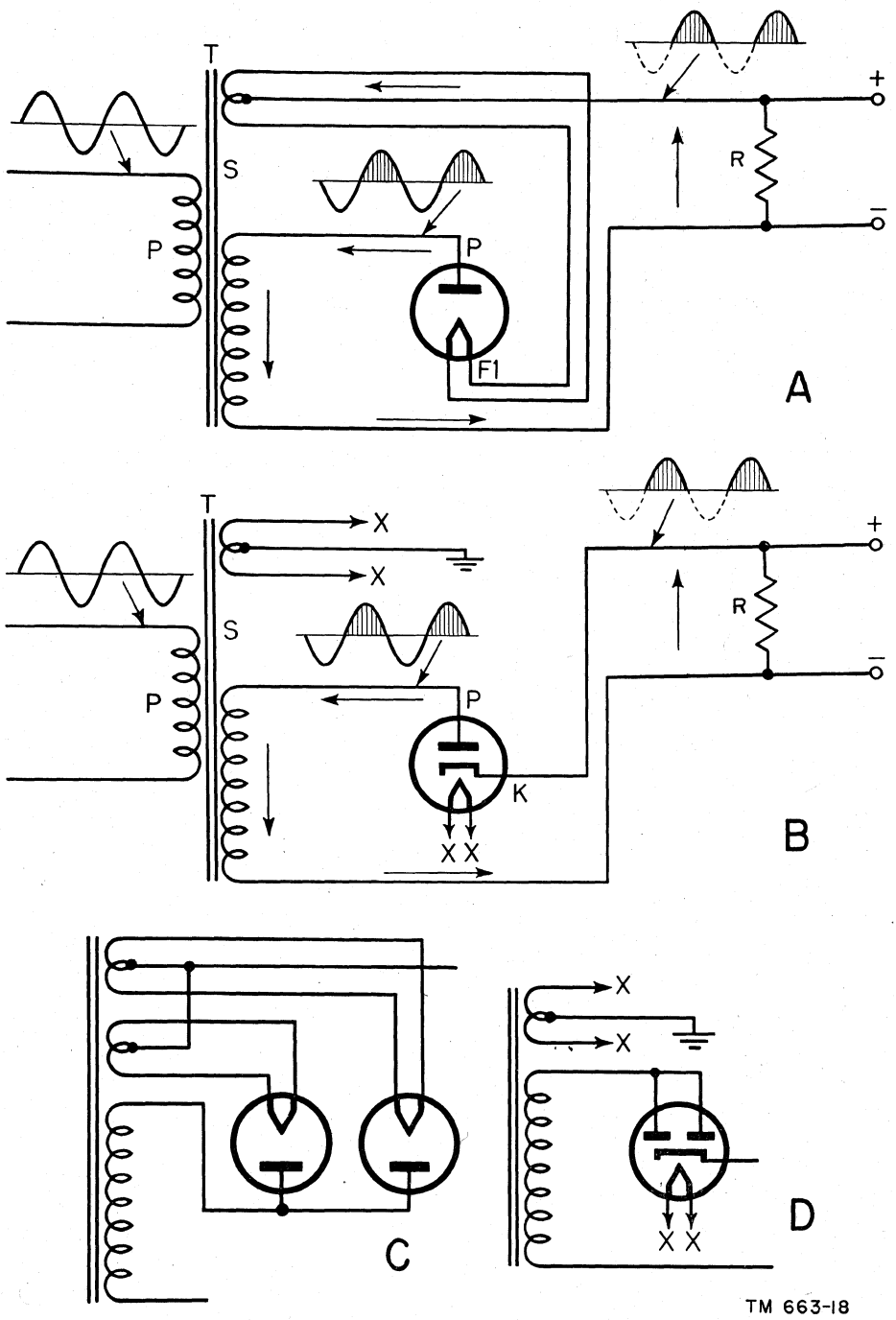

Figure 12. Basic half-wave rectifier circuit showing output waveform.

half of the value of the input voltage. Actually, the average value of the output voltage will be less than half owing to the loss caused by the internal voltage drop of the tube.

b. The average value of the d-c output voltage (fig. 13) will be less than half the input voltage. To determine the voltage a d-c voltmeter will read when connected directly across the output of the half-wave rectifier in A, figure 12, assume the following conditions: The necessary filament voltage is applied to the tube for normal operation, the power transformer has a step-up ratio of 1 to 4 and

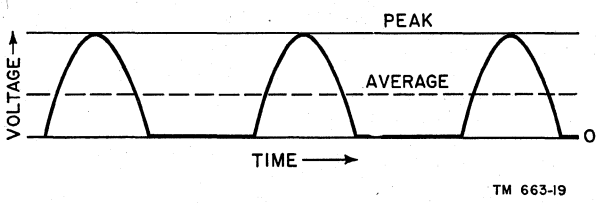

Figure 13. Half-wave rectification showing peak and average voltages at output of rectifier.

with 115 volts applied across the primary, 460 volts will appear across the high-voltage secondary. This voltage is the rms or effective value, and must be converted to peak value. The formula for peak voltage is:

$$E_{peak}=1.414\times E_{rms}.$$

Substituting the values mentioned above:

$E_{peak}=1.414\times 460=650$ volts, approximately.

This 650 volts is the voltage obtained at the peak of the rectified pulse (fig. 13). All voltages are measured with relation to the zero reference line which corresponds to the bottom of the secondary winding.

c. When a voltmeter is connected across the output of the rectifier, the inertia of its movement will not allow the voltmeter needle to respond to the rapidly changing pulses of rectified current. It will act as a mechanical integrator, however, and will have a displacement which is proportional to the time average of the applied voltage wave. If a full sine wave were applied to the voltmeter, the displacement of the needle would be zero, because the time average of the sine wave is zero. Since only positive half-cycles will activate the voltmeter, positive displacement will result, indicating the average d-c voltage. Neglecting the drop across the tube, the average voltage is determined from the formula:

$$E_{average}=\frac{1\times E_{peak}}{\pi}$$

or, $\frac{1}{3.14}\times 650=207$ volts.

This 207 volts is the average voltage a d-c voltmeter would read when placed across the output of a half-wave rectifier. Consequently, it is apparent that approximately only 45 percent of the rms secondary voltage appears as d-c in the output of the half-wave rectifier *before filtering.*

d. This half-wave rectified voltage is useless without filtering for most applications, since it is far from being the pure d-c required. A measure of its departure from the required state can be had by analyzing the waveform into the average d-c component we have just calculated. Ripple components (pulsations), which are multiples of the input power frequency and whose amplitudes determine the departure of the waveform from pure d-c in the half-wave rectifier also must be considered. The ripple components are obviously so large that it is pointless to calculate them; the predominant ripple component is the frequency of the input power. Ripple is discussed in detail in paragraph 55*c*(1).

19. Application

Half-wave rectifiers find wide application in some a-c/d-c radio equipment, oscilloscope high-voltage supplies, and many low-voltage power supplies. Low-voltage battery chargers of the Tungar type also use half-wave rectifiers, but special transformers are required to prevent core saturation because of the high d-c current developed. For reasons of economy in space and cost, metallic half-wave rectifiers generally are used in small a-c/d-c equipment with limited power requirements.

Section III.—FULL-WAVE RECTIFIER

20. Circuit Arrangement

The full-wave rectifier, fundamentally, consists of two half-wave rectifiers which function on opposite alternations of the applied input voltage. Two individual rectifying units can be used, or the two rectifying elements can be combined in one device (A and B, fig. 14). In the full-wave duodiode rectifier tube, two diode sections are inclosed in a single evacuated envelope. Two individual diode rectifiers are shown in A and two diodes combined in a single tube in B. Filament voltage is obtained from a separate winding on the transformer, as before, but the secondary coil that feeds the full-wave rectifier plates is center-tapped at *C*. This is to provide two equal voltages, *E*1 and *E*2, for the operation of the two half-wave elements.

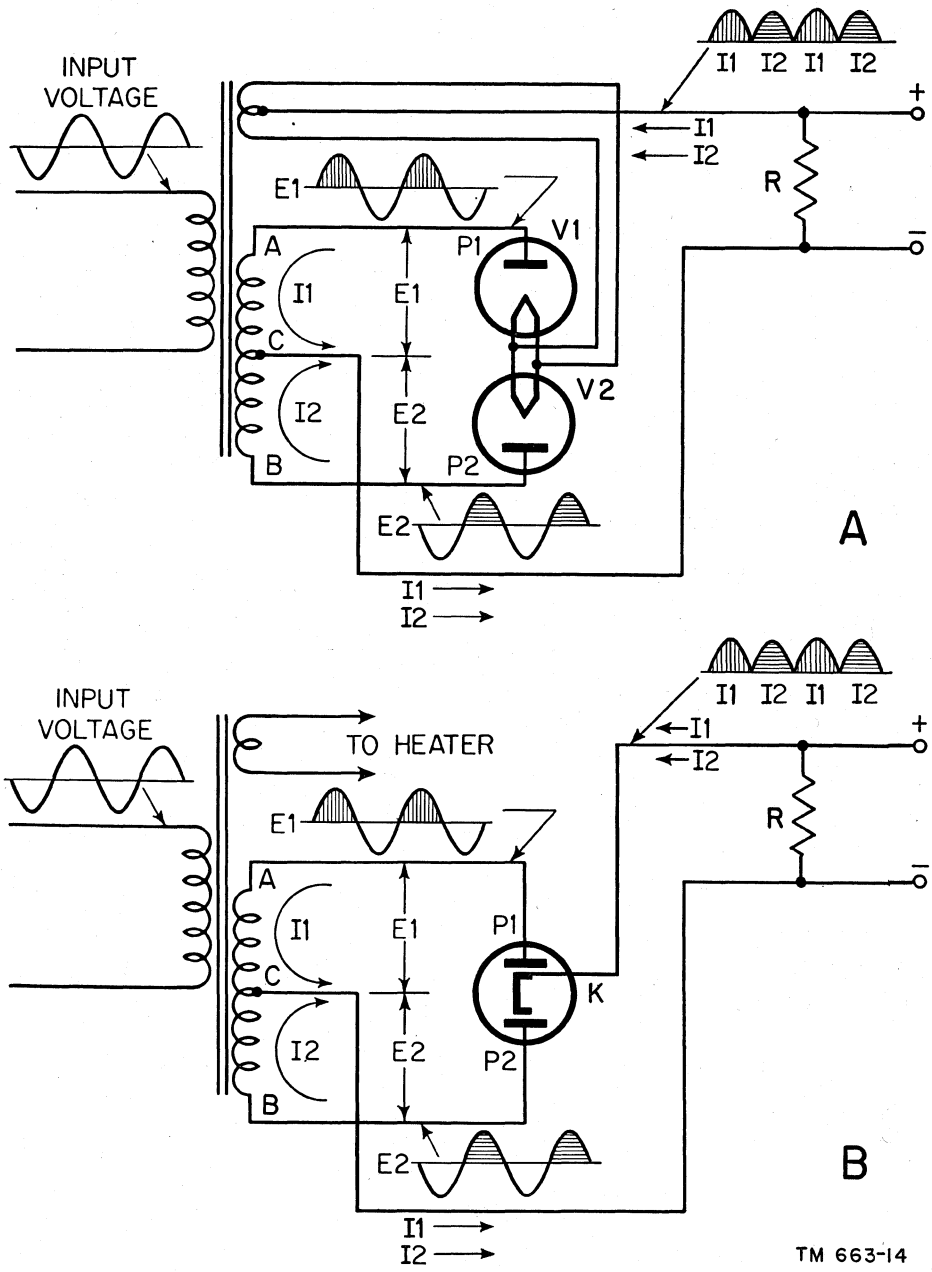

Figure 14. Basic full-wave rectifier circuit with output waveform.

21. Full-wave Rectifying Action
(fig. 14)

The average d-c voltage delivered to the output can be increased if the applied voltage can be rectified on both the positive and the negative peaks of the alternating current. To accomplish this, the transformer secondary is tapped at its electrical midpoint, C, so that the voltages between each end of the coil and the midpoint are of equal value, and 180° out of phase with each other. Amplitude and phase of the two voltages are shown by the two voltage waveforms labeled $E1$ and $E2$. These waveforms indicate that for any instant the voltage at one end of the secondary winding is exactly opposite in polarity to that existing at the other end. These two voltages, which alternately become positive and negative with relation to center tap C, are applied to the plates of the rectifier tube. With a negative alternation applied to

the transformer primary, the first alternation of secondary voltage, $E1$, is positive (by transformer action). Plate $P1$ then becomes positive with relation to the cathode and this half of the rectifier conducts current. A current pulse, indicated as $I1$, flows through the output circuit, R, and the upper half of the secondary coil (points A and C). During the second alternation of the first cycle of applied voltage, the polarity of the secondary voltage reverses, making plate $P1$ and point A on the transformer secondary negative, while point B and plate $P2$ of the other rectifier unit become positive. Current is cut off in rectifier $V1$, and a pulse of current $I2$ flows through $V2$, the lower half of the transformer secondary coil (points B and C and resistor R), in the direction of the arrows labeled $I2$. Therefore, it can be seen that conduction occurs alternately in each half of the full-wave rectifier in conformance with the changing polarity of the applied input voltage, but the direction of current flow through R is always the same.

22. Output Waveform

The result of full-wave rectification is shown in figure 14. The vertical-shaded pulses occur when the positive alternations of the input voltage appear at A; the horizontal-shaded pulses occur when the positive alternations appear at B. In the output waveform, all of these alternations appear above the zero reference line and since the alternations never reverse their polarity, full-wave rectification produces a d-c voltage which is pulsating at twice the frequency of the input voltage. This is so because there are two alternations in each cycle and a current pulse is produced by each alternation. The rectified pulses are positive on each alternation because the current flow from the cathode or filament to the plate of the rectifier tube is always in the *same* direction. The cathodes are positive with relation to the center tap of the transformer regardless of which section is conducting.

23. Peak and Average Values of Output Voltage

a. Because both alternations of the input voltage cycle are utilized in the full-wave rectifier, the average output voltage is twice that of the half-wave system. Allowing for the voltage drop across the tube (or tubes), the voltage across the output of the power supply is approximately 90 percent of the rms potential applied to either rectifying section (fig. 15). This figure does not apply to gaseous rectifier tubes, in which the efficiency is somewhat higher.

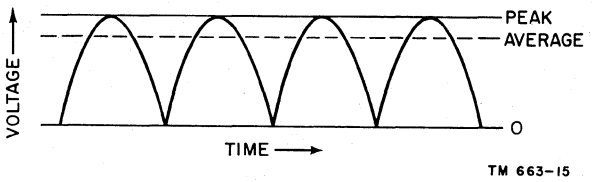

Figure 15. Full-wave rectification showing peak and average voltages at output of rectifier.

b. An example of the peak and average voltages obtained from the full-wave rectifier is shown in figure 14. A transformer with a higher step-up ratio is assumed, since only half of the total secondary voltage is applied to each diode of the rectifier tube. With an applied input of 115 volts and a step-up ratio of 1 to 8, 920 volts appears across the full secondary winding and 460 volts is applied to each diode. Again a d-c voltmeter is connected across the rectifier output.

c. Since only one-half of the secondary is being used at a time, the peak voltage is determined by using half of the available voltage on the winding, or 460 volts rms. From the peak voltage formula, this becomes:

$$E_{peak}=1.414\times E_{rms}=1.414\times 460=650 \text{ volts, approximately.}$$

This value is the same as that obtained for the half-wave rectifier. There are now two pulses in every cycle of input voltage instead of one. This means that the average value of voltage measured by the voltmeter will be greater than before since the output is now double that of the half-wave rectifier, or:

$$E_{average}=E_{peak}\times\frac{2}{\pi}=650\times\frac{2}{3.14}=414 \text{ volts.}$$

This value is approximately 90 percent of the rms input voltage.

d. Although the average d-c output voltage is greater for the full-wave rectifier, and the ripple components are much less, they are still so large that the voltage is useless for most applications. The ripple component is twice the frequency of the input voltage, or 120 cps because there are two rectified pulses for each cycle instead of one as in the half-wave rectifier.

24. Application

Full-wave rectifier systems generally are used in the power supplies of communications equipment. High efficiency and flexibility in providing a wide range of output voltages with moderate currents are the principal reasons for their popularity. The full-wave rectifier is used extensively in battery chargers since transformer design is not so critical as in half-wave rectifiers. This is so because the direct current flows alternately through the two halves of the center-tapped power transformer and sets up opposing magnetic fields, reducing the danger of d-c saturation of the transformer core.

Section IV. BRIDGE RECTIFIER

25. Circuit Arrangement

When four half-wave rectifier elements are connected as in figure 16, the circuit is called a bridge rectifier. The a-c input voltage is applied to two diagonally opposite corners of the bridge and the resulting d-c output voltage is taken from the two remaining corners. In this manner, full-wave rectification is obtained by utilizing the entire voltage across the secondary winding of the power transformer. Resistor R, connected across the output of the bridge rectifier, represents the load on the circuit.

26. Bridge-Rectifying Action

a. Referring to figure 16, assume 1½ cycles of applied a-c input voltage. Point A on the transformer secondary now becomes positive with relation to B during the first alternation. The positive voltage at A is applied to the plate of $V3$, causing this tube to conduct. Simultaneously, the negative voltage at B is applied to the cathode of $V1$, making the cathode highly negative with relation to the plate of $V1$ and causing this tube to conduct also. The path of the current flow through the circuit is indicated by the solid arrows.

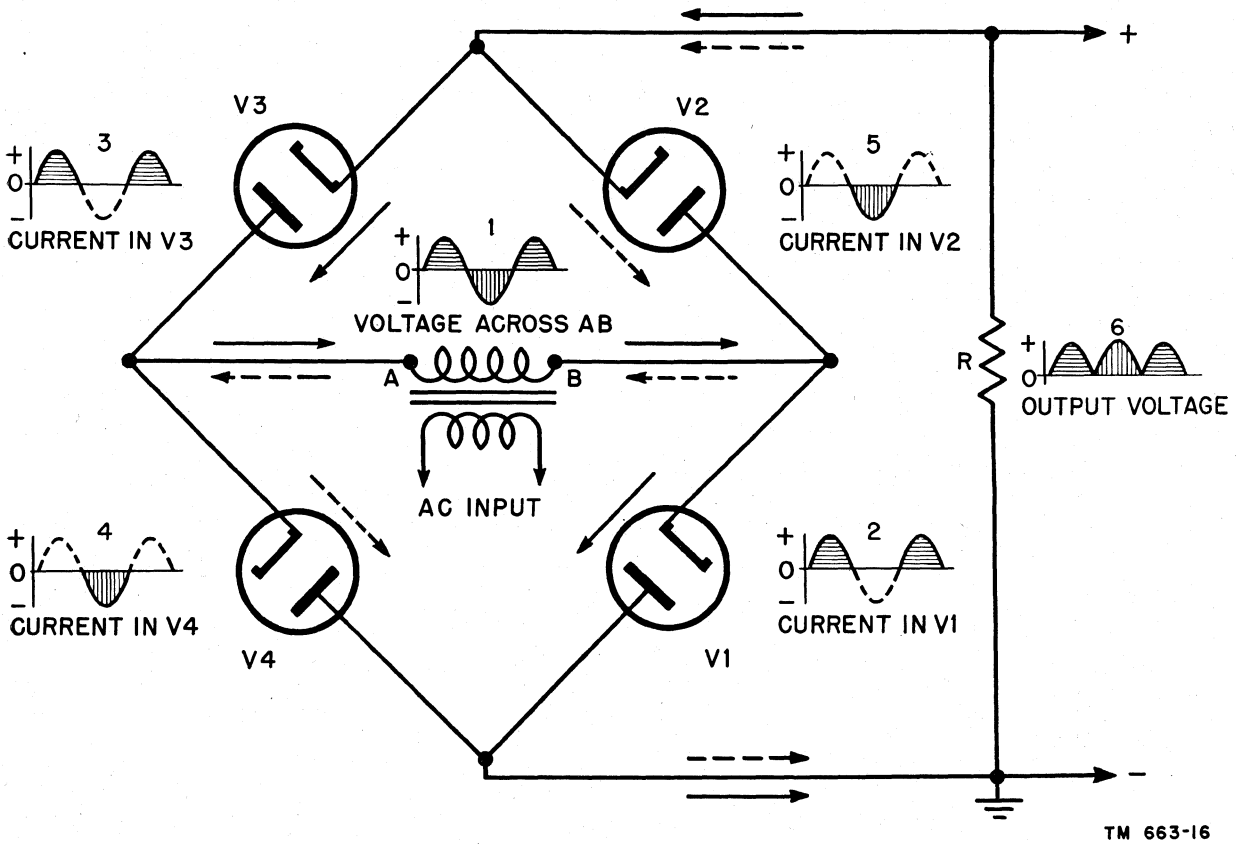

Figure 16. Bridge-rectifier circuit utilizing full voltage of transformer secondary.

b. Tracing this path from *A*, the current flows through the transformer secondary to the cathode of *V*1 and across this tube to the plate. From the plate of *V*1, it continues to the low end of the load resistor, R, passing up through the resistor to the cathode of *V*3. Current flows through *V*3 to the plate of the tube and thence back to *A* on the transformer, completing the circuit. During this half-cycle of applied a-c voltage, a pulse of d-c voltage occurs across the load.

c. On the next half-cycle of applied voltage, the polarity is reversed; *B* becomes positive and *A* negative. This makes the plate of *V*2 positive and the cathode of *V*4 negative, and satisfies the conditions for current flow through these tubes. This current flow is indicated by the dotted lines in figure 16. Tubes *V*1 and *V*3 now are cut off.

d. The path of the current flow now can be traced easily. The flow of current in the load is always in the same direction, producing a voltage pulse in the output of the same polarity as that of the preceding half-cycle. Since the plate of *V*3 is highly negative and the cathode of *V*1 is positive with relation to its plate, no current flows through this part of the circuit. It is evident that, since current flows through the load during the full cycle of applied a-c voltage, full-wave rectification occurs.

27. Output Waveform

The output waveform of the bridge rectifier shows a pulsating d-c voltage utilizing both alternations of the applied a-c voltage cycle (fig. 16). The alternations are the same as in the basic full-wave rectifier discussed in paragraph 22.

28. Average Value of Output Voltage

a. The bridge rectifier is a full-wave circuit, and the output voltage obtained from it is nearly twice the value of that of a conventional full-wave circuit using a center-tapped transformer secondary. In the conventional full-wave circuit, only the voltage existing across one end of the secondary and the center tap is rectified during each alternation. In the bridge circuit, the full voltage existing across the entire secondary is rectified for each alternation. Therefore, with equal transformer ratings, the output voltage from the bridge circuit will be twice that of the conventional full-wave circuit, less the voltage drop across the additional rectifier tubes.

b. For example, assume that for any instant 800 volts exists across the entire transformer secondary. In the conventional full-wave circuit, only the voltage existing between one end of the transformer and center tap is applied to each half-wave section. This means that only 400 volts is available for rectification with each alternation. The total voltage in the output of this circuit is then 400 volts, less the internal voltage drop of the tube, and this same value will be produced with each succeeding alternation. In the bridge circuit the transformer, having no center tap, alternately delivers the full 800 volts to each half of the rectifier circuit. The output voltage now is 800 volts, less the internal voltage drop across the tubes, or approximately twice as much as in the previous case.

29. Application

a. The bridge rectifier is used when it is desired to utilize the voltage across the full secondary of the transformer. It will be found in some high-voltage applications, but because of the additional tubes required and the three separate filament tranformer windings needed, applications using electron tubes are few. The three filament transformers or windings are required because the filaments of the tubes are not all at the same potential. These transformers must be well insulated from each other and from ground because of the high potentials to which they are subjected. Consequently, metallic rectifiers usually replace electron tubes in most bridge-rectifier applications.

b. The bridge circuit finds wide use in electrical measuring equipment and, also, is used in many low-voltage plate supplies. In these applications, the electron tubes generally are replaced by metallic rectifiers of the copper-oxide or selenium type. These metallic rectifiers have the advantage of occupying a small space and they do not require filament power.

Section V. METALLIC RECTIFIERS

30. Physical Characteristics

a. Metallic rectifiers, sometimes called metallic-oxide, or dry-disk, rectifiers, are constructed of metal plates upon which has been deposited a thin layer of metallic oxide or nonmetallic substances, such as selenium. These substances exhibit a nonlinear characteristic with relation to current flow, since current passes easily through the plates in one direction, but not in the opposite direction. Because of this property these units can be used as rectifying devices. Figure 17 shows different types of metallic rectifiers, which are schematically represented in figure 18. In the schematic, an arrowhead points in the direction that current flows through the metallic rectifier, and corresponds to the cathode of an electron tube.

b. Several metallic and nonmetallic substances possess nonlinear characteristics as regards current

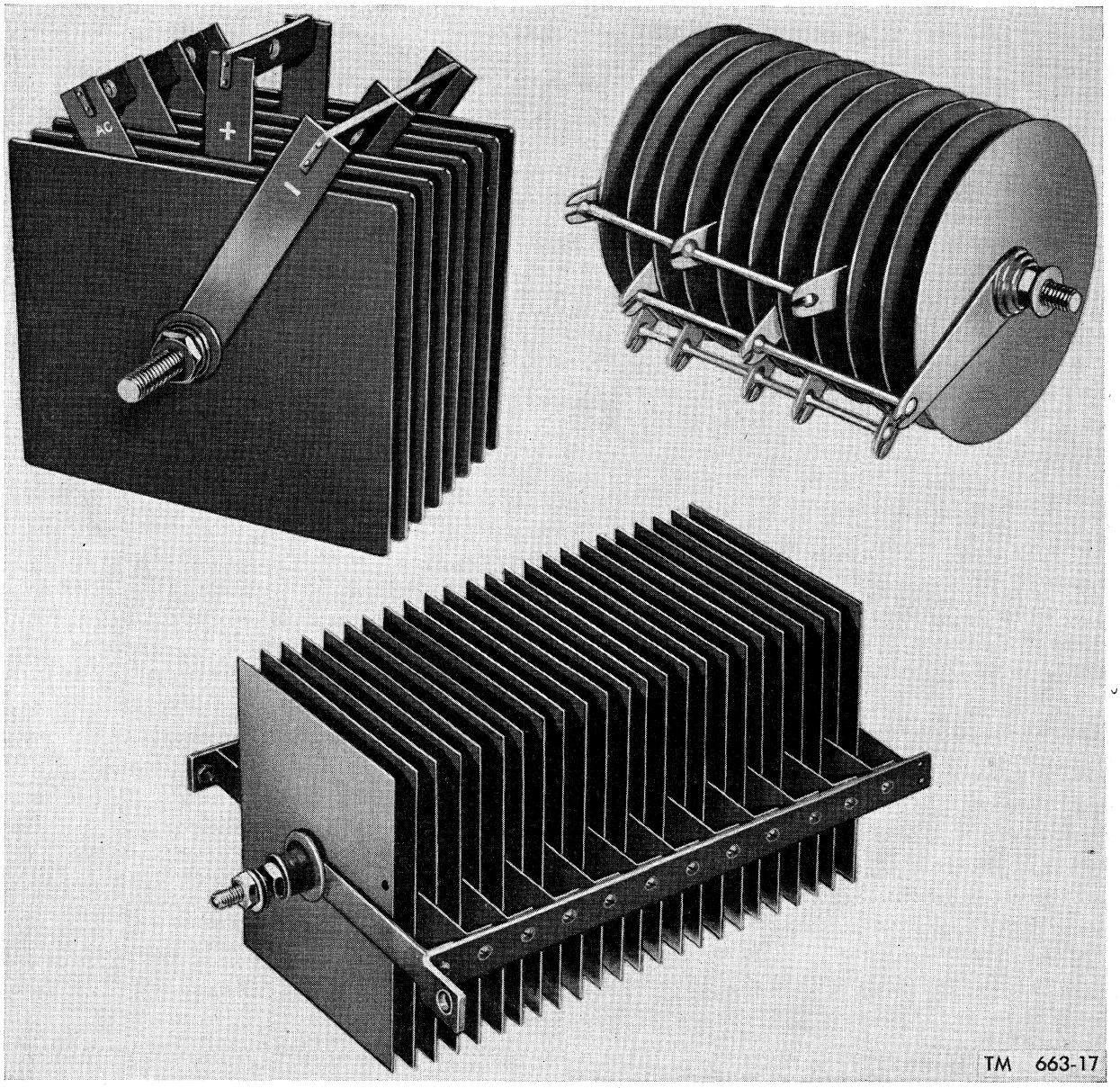

Figure 17. Various types of metallic, or dry-disk, rectifiers.

flow, but the most widely used are selenium, copper-oxide, and copper-sulphide. Selenium rectifiers are the most extensively used, having supplanted other types in nearly all applications; in this treatment of metallic rectifiers, emphasis will be placed on the selenium rectifier. The two other types will be treated briefly.

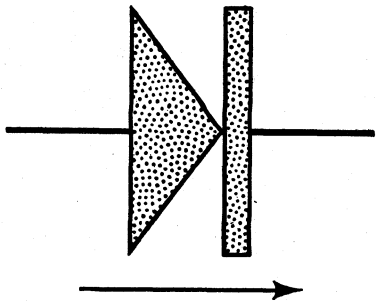

Figure 18. Schematic representation of metallic rectifier.

c. Since the deposited films on the individual metal plates are microscopic in thickness, the voltage that each single element can sustain without rupture is relatively low, being somewhat less than 25 volts peak. To overcome this limitation when higher voltages are to be rectified, several elements are connected in series (fig. 17). The total number of dry-disk elements in series determines the peak voltage that the completed rectifier can sustain, and the individual area of the elements determines the current-carrying capacity. The elements can be assembled in series-parallel combinations to meet a wide variety of voltage and current requirements.

31. Types of Metallic Rectifiers

a. Copper-Oxide Rectifier. In the construction of copper-oxide rectifiers, a thin film of cuprous oxide is formed on one surface of a small, thin, copper disk. A stack of these disks then is assembled on an insulated rod with lead or other soft metal washers spaced alternately between them. The entire assembly then is tightly clamped together to provide rigidity and maximum efficiency of electrical contact between the conducting elements. Cooling fins to radiate excessive heat can be spaced between the disks if necessary. The direction of electron flow through the copper-oxide rectifier is from the copper to the copper oxide.

b. Copper-Sulphide Rectifier. The copper-sulphide rectifier is similar physically to the copper-oxide rectifier. A thin magnesium disk is coated with a film of cupric sulphide and several such disks are formed together into a tightly clamped assembly. This rectifier has a low breakdown voltage, and operating temperatures must be maintained within limits. The device is designed for a safe operating temperature of 90° C., and higher temperatures can be tolerated for short periods of time only. The copper-sulphide rectifier has a tendency to deteriorate after long periods of disuse, particularly if left idle in a moist atmosphere. Failure can be detected by a strong odor caused by the liberation of sulphur dioxide. The direction of electron flow through the copper-sulphide rectifier is from the metal disk to the copper sulphide.

c. Selenium Rectifiers (fig. 20).

(1) The selenium rectifier has attained widespread use and has largely replaced the copper-oxide and copper-sulphide rectifiers. In the construction of the selenium rectifier, a layer of selenium is deposited on a thin aluminum or steel base plate (fig. 19). The entire surface of the disk is covered with selenium except a small area at the center and a narrow edge around the rim of the disk. These points later are coated with insulating compound. After the selenium is deposited, a conducting alloy of a low melting point is sprayed over the surface and becomes the front electrode. In the processing, a barrier layer is formed at the surface of contact between the selenium deposit and the front electrode. This barrier can be considered as having no free electrons, in itself, yet having the property of permitting free electrons to pass in either direction. The selenium is a poor conductor, having relatively few free electrons, but an abundant supply of free electrons is available in the front electrode. This property of the selenium disk establishes the conditions for rectification of an applied a-c voltage.

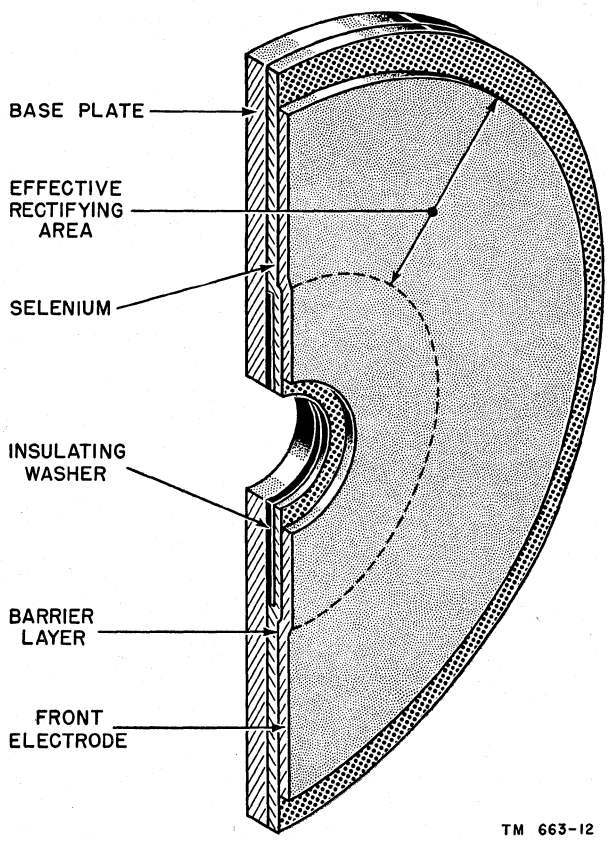

Figure 19. Cross section of a selenium-coated disk.

(2) The action is as follows: The selenium deposited on the metal disk becomes one terminal of the rectifier, and the front electrode becomes the other terminal. On one alternation of the applied voltage, the free electrons pass readily from the front electrode through the barrier and selenium layers to the metal disk and on through the circuit. However, on the reverse alternation, a minimum of current is passed, owing to the relatively small number of free electrons available in the selenium layer.

(3) The assembly of a stack of selenium rectifier disks is not as critical as the assembly of copper-oxide disks, because extremely rigid clamping is not required. Pressure sufficient to maintain good electrical contact and firm assembly is all that is needed. Too much pressure can damage the front electrode. After assembly, the stack is coated with some type of protective finish, such as organic paint or synthetic varnish, to eliminate adverse effects of moisture or vapor penetration. Some attempts have been made to obviate the effects of atmospheric conditions by sealing the assembled unit in oil. This method of protection, while desirable, has the disadvantage of increasing the weight of the unit materially.

(4) Early selenium rectifiers were limited to a maximum of 14 volts rms per plate. Later development has resulted in an increase in ratings to 26 volts per plate, and higher ratings are anticipated. A plot of forward resistance versus voltage is shown in figure 21, and current versus voltage characteristics are shown in figure 22. These ratings are based on an operating temperature of 35° C.

(5) The maximum temperature at which the selenium rectifier can be operated is limited by the melting point of the alloy of which the front electrode is composed. This temperature is also the approximate limiting temperature of the selenium. Breakdown is caused by the liberation of selenium dioxide and is accompanied by an odor similar to that of rotten eggs. Selenium rectifiers are susceptible to failure in the presence of mercury vapor and should not be stored in close proximity to mercury-vapor tubes where any breakage of the latter is possible. In equipments utilizing both selenium and mercury-vapor rectifiers, care must be taken to insure that any free mercury liberated by accidental breakage of the tubes is removed as quickly as possible and the unit component thoroughly cleaned with compressed air, if this is available.

32. Circuit Arrangement

Figure 23 shows metallic rectifiers being used in the three rectifier circuits previously discussed—half-wave in A, full-wave in B, and bridge in C. Frequently, the transformer is not used, the line voltage being applied directly at points *A* and *B*.

33. Rectifying Action

a. The rectifying action of metallic rectifiers is exactly the same as that discussed under half-wave, full-wave, and bridge rectifier circuits using electron tubes. In the half-wave circuit in A,

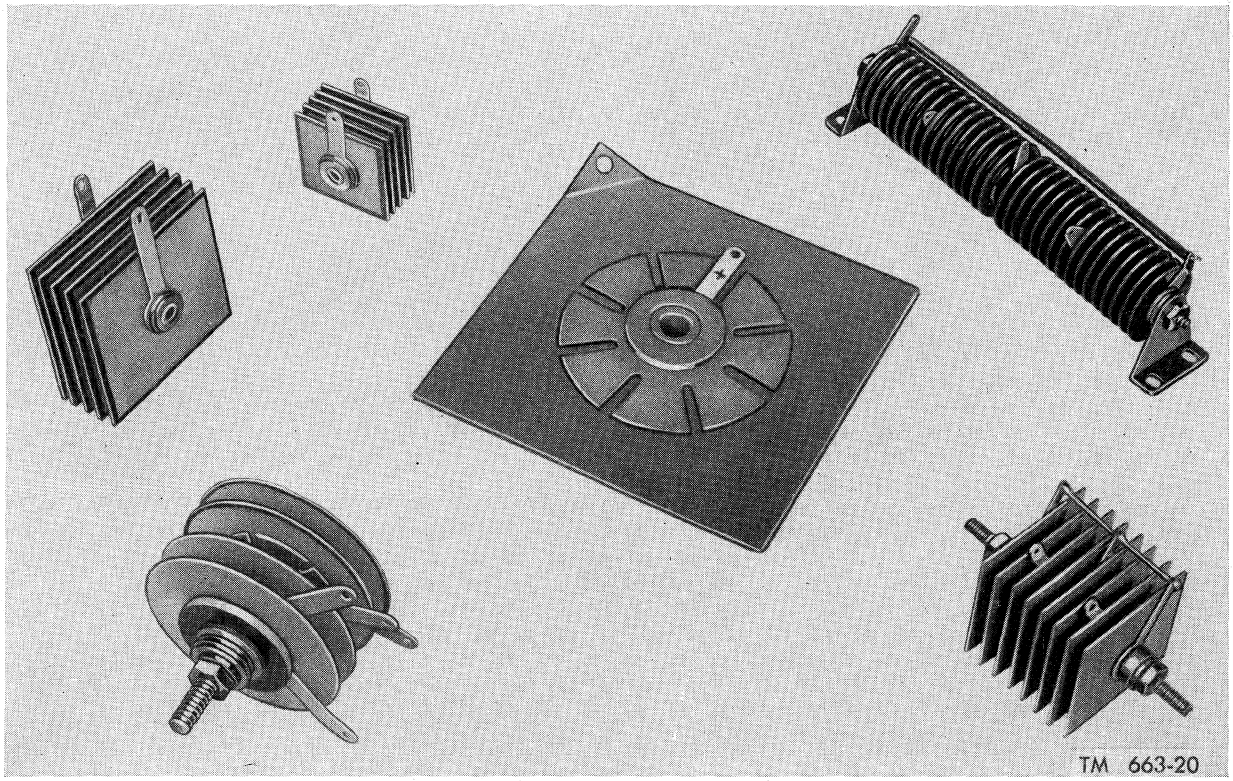

Figure 20. Various types of selenium rectifiers.

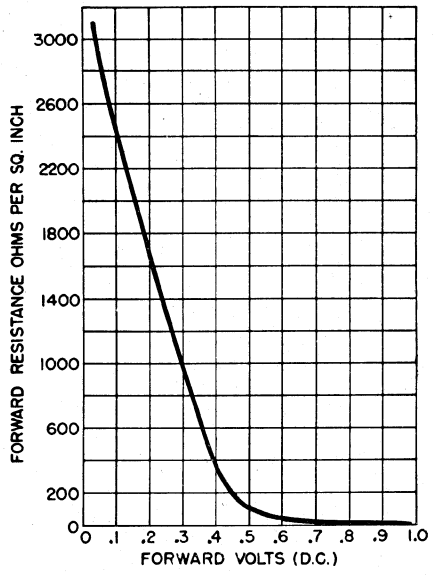

Figure 21. Characteristic curve showing forward d-c volts versus forward resistance.

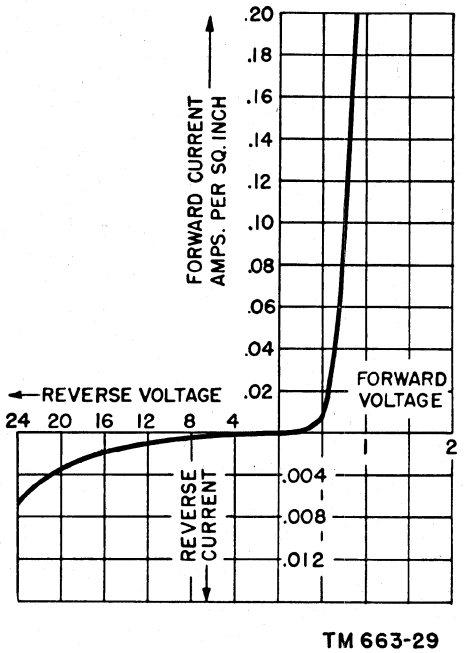

Figure 22. Characteristic curve showing current versus voltage.

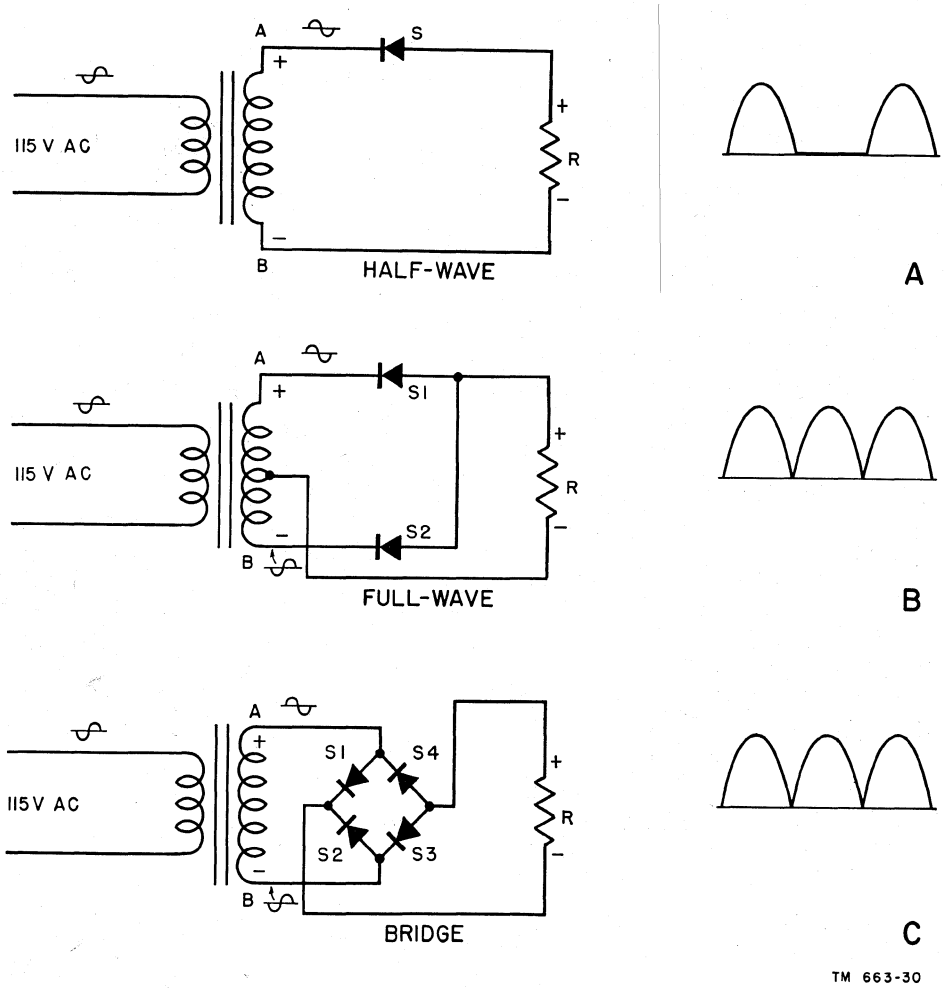

Figure 23. Metallic rectifiers shown in half-wave, full-wave, and bridge rectifier circuits.

figure 23, a pulse of current flows through the output circuit when a positive alternation exists at A on the transformer secondary. On the next cycle of applied voltage, A becomes negative with relation to B and no current flows through the circuit. Since current flows through the output circuit during half of each cycle, half-wave rectification occurs in the output.

b. Referring to B, figure 23, when A on the transformer secondary is positive, current flows from the transformer center tap through the filter and voltage-divider load, through the top selenium rectifier, $S1$, as indicated by the arrow, and back to A. This action produces a voltage pulse in the output circuit. During the next alternation, when point B becomes positive, current flows from the center tap through the load, the lower selenium rectifier, $S2$, and back to B on the transformer. This produces a second pulse in the output, and the action continues as long as input voltage is applied. The effect of this is to produce full-wave rectification in the output circuit.

c. In the bridge circuit of C, figure 23, current flows through alternate half-sections of the bridge circuit for each half-cycle of applied voltage. The selenium units, $S2$ and $S4$, conduct when A on the transformer secondary is positive, and $S1$ and $S3$ conduct when B becomes positive. In this manner, full-wave rectification is accomplished.

34. Output Waveform

The output waveform for each of the rectifier circuits described above is shown to the right of each diagram in figure 23. In half-wave rectification, shown in A, half of the applied input waveform appears in the output; the output waveforms of both B and C show the full applied voltage waveform.

35. Average Value of Output Voltage

The average value of output voltage differs in each of the circuits shown in figure 23. With half-way rectification only half of the applied voltage minus the voltage loss in the circuit appears in the output. The full-wave circuit of B produces twice the average rectified voltage available from the circuit in A. In the circuit of C, the output voltage is twice the amplitude of that in B when the same value of applied voltage exists across the transformer secondaries. Or, conversely, only one-half the value of applied input voltage is required in C to produce the same value of output voltage produced in B.

36. Application

a. As stated formerly, metallic rectifiers are used widely in many applications. Copper-oxide and copper-sulphide rectifiers used in electronic test and measuring instruments to rectify a-c voltages for meters and other indicators gradually are being replaced by selenium rectifiers.

b. The selenium rectifier is the most commonly used metallic rectifier. It ranges in physical size from small units, consisting of a few disks which can be held between thumb and forefinger, to the large combinations of devices incased in oil-filled containers. Its application is practically unlimited; it is used to supply the rectified low voltage and relatively high current of battery charges and other equipment, as well as the intermediate and high voltages required by receivers, transmitters, and other electronic equipment.

c. Selenium rectifiers are used in single-phase or polyphase circuits and as half-wave, full-wave, and bridge rectifiers. The bridge circuit is especially advantageous because the full voltage existing across an untapped transformer secondary can be utilized in full-wave rectification.

d. Selenium rectifiers require no filament voltages, are economical, easy to install, have a low heat dissipation, and the voltage drop across the rectifier is low. Their chief disadvantage is the limited current output, although this can be overcome to some extent by connecting the rectifiers in series, parallel, or series parallel.

Section VI. VOLTAGE DOUBLER

37. Purpose of Voltage Doubler

The term *voltage doubler* indicates that the function of the circuit is to provide twice as much voltage in the output as that applied to the input of the rectifier. This voltage doubling is obtained with half-wave rectifiers and filter capacitors arranged in special circuits. In the conventional voltage-doubler circuit (fig. 24) electron tubes are used as rectifiers, but the circuit is just as readily applicable to metallic rectifiers. Selenium rectifiers often are used in voltage-doubling circuits.

38. Circuit Arrangement

The circuit shown in figure 24 represents a common full-wave voltage-doubling circuit. The two capacitors, $C1$, and $C2$, are charged on alternate half-cycles and are so arranged that their discharge voltages add in the output. This circuit is capable of delivering, at the output of the power supply, a voltage which is nearly twice the peak voltage of the applied alternating voltage.

39. Rectifying and Doubling Action

a. Referring to figure 24, when A on the transformer secondary is more positive with relation to B, a voltage is impressed across $V1$ and capacitor $C1$ which are in series. Since the plate of $V1$ is more positive than its cathode, electrons are attacted to the plate and flow around the circuit as shown by the solid arrows. The source of the electrons must be capacitor $C1$ and the electrons that leave the upper plate flow through $V1$ and accumulate on the lower plate. Therefore, the upper plate of $C1$ becomes positive relative to the lower plate by a voltage equal to the peak value of the applied input voltage.

b. During the next half-cycle, when $V1$ does not conduct, $C1$ discharges slightly by allowing a few electrons to flow from the lower plate of $C1$ through the transformer, $V2$, resistors $R2$, $R1$ and to the upper plate of $C1$. While $C1$ is discharging in this manner, capacitor $C2$ is being charged by electron current that flows through $V2$. B is positive with relation to point A on this half-cycle. The charging current for $C2$ flows in the

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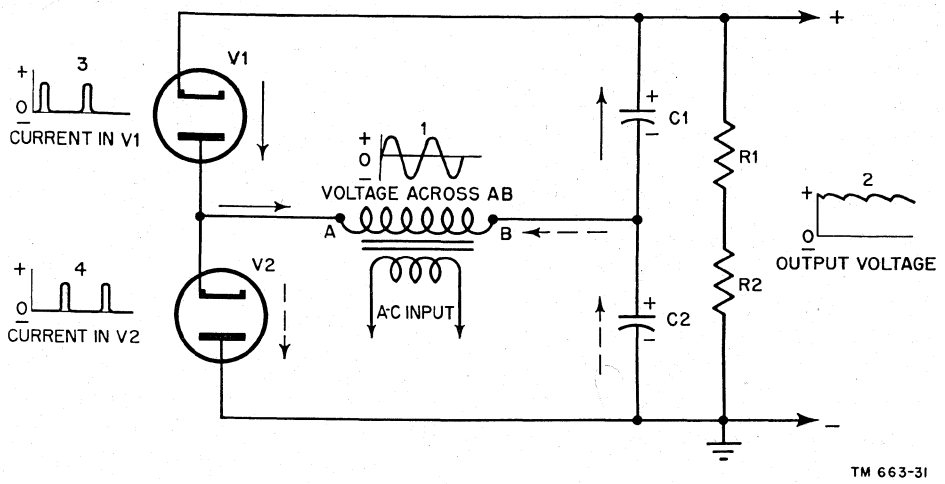


Figure 24. A conventional voltage-doubler circuit using two half-wave rectifier tubes to provide full-wave rectification.

direction of the dotted arrows and charges $C2$ to a value equal to the peak input voltage. Since $C1$ and $C2$ are in series across the output, the available voltage is equal to the sum of the charges existing across the two capacitors. The values of $C1$ and $C2$ should be as nearly equal as possible and not less than 16 uf (microfarads). In general, the larger the capacitance the better the reguation. However, the larger the capacitance the more charging current will flow in the circuit, and this current must not exceed the peak plate current ratings of the rectifier. Since the value of capacitance is large for $C1$ and $C2$, the output voltage has a small ripple component (2 of fig. 24). The waveforms in figure 24 illustrate the action occurring at the indicated points in the circuit.

c. Resistors $R1$ and $R2$ have a very large value, generally about 5 to 10 meg (megohms) each. These resistors are used to allow the charge on the capacitors to leak off when the transformer is not energized. This is necessary as a safety measure to prevent injury from the high voltage existing across the capacitors after the circuit has been turned off.

d. A half-wave circuit arrangement for voltage doubling (fig. 25) is the cascade voltage doubler, which functions as follows: Assume initially that tube $V2$ is disconnected from the circuit. When B of the transformer secondary is positive with relation to A, electrons flow from the cathode to the plate of $V1$. The direction of flow is shown by the dotted arrows. Electrons flow from the right-hand plate of $C1$, across tube $V1$, and through the transformer secondary to the left-hand plate of $C1$. The left plate of $C1$ now has an excess of electrons and the right plate has a deficiency; consequently, the right plate is highly positive with relation to the left plate. After a few cycles, capacitor $C1$ is charged to the peak value of the voltage existing across the secondary of the transformer.

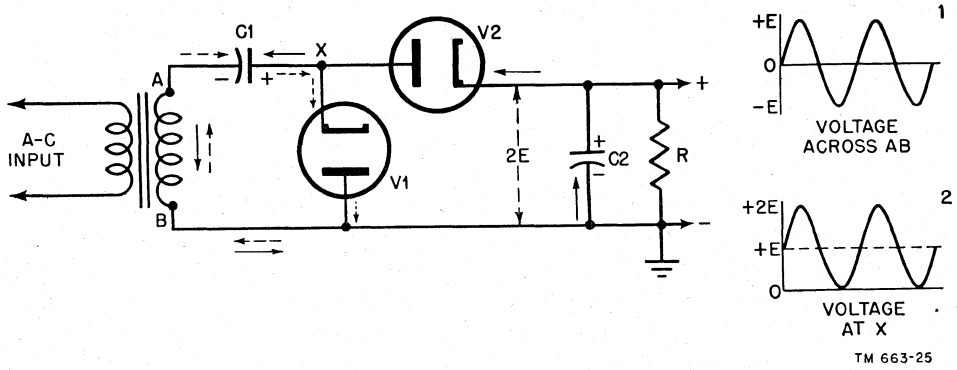


Figure 25. A cascade voltage doubler with half-wave rectification.

e. When A is positive and $C1$ is fully charged to the polarity shown and in series with the transformer secondary, the voltage between X and B will be nearly twice the peak value of the secondary voltage. Since the voltage at X fluctuates in value between zero and twice the peak input voltage, it can be shown that the voltage varies with relation to a shift in zero axis (2 of fig. 25). When the positive voltage at point X is applied to the plate of $V2$, a current flows through $V2$ and around the circuit in the direction of the solid arrows. This current charges capacitor $C2$ to the value of the peak voltage existing at X and the output voltage across $C2$ will be nearly twice the peak voltage across points A and B of the transformer secondary.

40. Output Waveform

a. The input and output voltage waveforms of the conventional voltage doubler are shown in 1 and 2 of figure 24; 3 and 4 show the direct relationship between the currents flowing in $V1$ and $V2$ and the applied input voltage. A current pulse flows through $V1$ on each positive half-cycle and through $V2$ on each negative half-cycle of the applied voltage. The output voltage waveform in 2 of figure 24 shows a pulsating d-c voltage, with very little ripple component, occurring at a rate equal to double the line voltage. The depressions in the waveform are caused by the slight discharge occurring in each capacitor during alternate half-cycles. These pulsations can be smoothed by means of additional filtering.

b. The waveform applied to $C2$ and R is a half-wave pulsation (1 of fig. 25). A comparison of the voltage existing at X and the input voltage across the transformer secondary is shown in 2. The voltage at X is a fluctuating d-c voltage varying in direct relationship with the applied a-c voltage. This voltage, however, never goes negative, but swings between zero and a peak of $+2E$. The total value of the applied ac is also $2E$ peak-to-peak, but half of this voltage is negative and half is positive for each cycle of input voltage.

41. Average Value of Output Voltage

The average value of voltage delivered by a voltage-doubling circuit is equal to the average value of the voltage across the charged capacitors. The exact voltage output will depend also on circuit losses and the internal drop in the rectifier tubes produced by the currents flowing through them. The value of current flowing depends on the load connected across the output. Voltage regulation in this circuit is poor because the value of voltage available in the output is a function of the current drawn by the load.

42. Application

The application of voltage-doubler circuits is limited to uses where the average current drawn by the load is small. This is easily explained with relation to the charging capacitors in the conventional doubler circuit (fig. 24). The energy delivered to the load must come from discharging the capacitors $C1$ and $C2$ in series. If a large current is drawn, the voltage across $C1$ and $C2$ falls greatly. However, if these capacitors are large, 16 μf and upward, a large current can be supplied with reasonably good voltage regulation if the load is on for only a few microseconds at a time. When the capacitors are large in value, the rectifier tubes may be damaged by the excessive peak current that flows during the short period of conduction. To protect the rectifier tubes in such cases, limiting resistors of a few thousand ohms are placed in the plate circuit of each tube.

Section VII. VOLTAGE MULTIPLIERS

43. Purpose

As the name implies, the purpose of a voltage-multiplier circuit is to multiply the applied input voltage to the value required by the output load circuit. Basically speaking, the voltage-doubler circuits described in the preceding section are multiplying circuits; this term, however, usually is reserved for circuits where the voltage is to be multiplied three or more times.

44. Circuit Arrangement

The voltage-tripler circuit in figure 26 consists essentially of the cascade voltage doubler discussed in paragraph 39*d*, plus a half-wave rectifier cir-

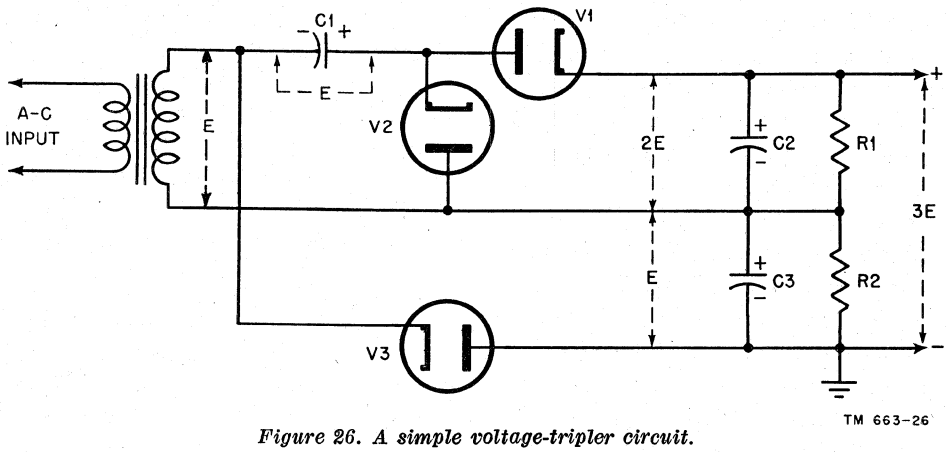


Figure 26. A simple voltage-tripler circuit.

cuit consisting of tube $V3$, capacitor $C3$, and resistor $R2$. With an input voltage E applied to the circuit, the output voltage appearing across $R1$ and $R2$ in series is three times E. Cascade voltage doublers can be combined in series arrangements to provide even higher voltage multiplication. A voltage-quadrupler circuit, consisting of two cascade voltage doublers in series, is shown in figure 27. The output from this arrangement provides approximately four times the peak value of the input voltage.

45. Rectifying Action

a. In figure 26, tubes $V1$ and $V2$, comprising the cascade voltage doubler, produce across $C2$ a voltage which is twice the peak voltage applied at the input, less the voltage drop in the tubes. During the time $V2$ is conducting $V3$ is conducting also, and capacitor $C3$ is charged to a value equal to the peak of the applied voltage from the transformer. With a value of $2E$ existing across $C2$, and of $1E$ across $C3$, the total value of voltage existing across the two series capacitors is $3E$. This voltage is nearly three times the peak input voltage less the voltage drop in the tubes.

b. Because of the asymmetry of the circuit arrangement, the pulsating or ripple frequency corresponds to the line frequency. Therefore, the output voltage assumes the characteristics of half-wave rectification.

c. In the voltage-quadrupler circuit of figure 27, two cascade voltage doublers are arranged so that input voltages are applied from a common source and the two output voltages are added in series.

d. The operation of this circuit is as follows:

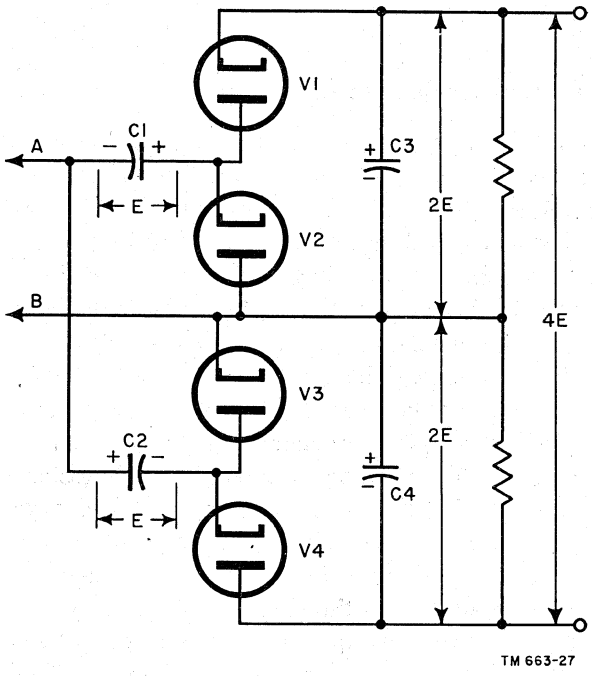


Figure 27. A voltage-quadrupler circuit.

(1) When the input voltage (fig. 27) on B is positive and A is negative, a current flows through $V2$ charging $C1$ to a value, E, equal to the peak line voltage minus the drop across $V2$. The polarity of the charge on $C1$ is such that when the next alternation occurs A becomes positive and B becomes negative; the line voltage then will add to the voltage across $C1$ and cause $V1$ to conduct, charging $C3$ to a value equal to $2E$ minus the voltage drop across $V1$. At the same instant the

cathode of $V3$ is negative with relation to its plate by the amount of the line voltage and $V3$ conducts, charging $C2$ to a voltage equal to the peak line voltage minus the voltage drop across $V3$, and to the polarity shown.

(2) On the next alternation line A is negative, line B is positive, and two events occur simultaneously. The line voltage is of such polarity that it adds to the voltage across $C2$ and the cathode of $V4$ becomes negative with relation to its plate, causing $V4$ to conduct and charging $C4$ to a voltage equal to $2E$. The plate of $V2$ being positive, the tube conducts and again charges $C2$.

(3) On one alternation of the cycle, $V1$ and $V3$ conduct, charging $C3$ to a value nearly equal to twice the line voltage, and $C2$ charges to a value equal to the line voltage. On the other alternation $V2$ and $V4$ conduct, charging $C4$ to a voltage nearly equal to twice the line voltage and $C1$ charges to a value equal to the line voltage.

(4) The total voltage appearing in the output of the circuit is the sum of the voltages existing across the two capacitors, $C3$ and $C4$, which is $4E$. The output voltage waveform has the characteristics of full-wave rectification.

Section VIII. SUMMARY AND REVIEW QUESTIONS

46. Summary

a. A rectifier changes alternating current into direct current.

b. The two most common types are electron tubes and metallic rectifiers.

c. Maximum peak inverse voltage is the largest negative voltage that can be applied to a rectifier when it is not conducting.

d. Electron-tube rectifiers are of two types, high-vacuum and gaseous.

e. The output of a half-wave rectifier is a d-c voltage pulsating in step with the frequency of the input voltage, since only half-cycles are rectified.

f. Full-wave rectifiers utilize the full cycle of input voltage; therefore, pulsations are twice the frequency of the input voltage.

g. The average voltage output of a full-wave rectifier is twice that of a half-wave circuit.

h. Four half-wave rectifiers are used in a bridge-rectifier circuit.

i. In bridge rectification, the total voltage across the transformer secondary is utilized; therefore, the output voltage is this value less the voltage drops in the circuit

j. The selenium rectifier is the most extensively used of the metallic rectifiers.

k. Voltage doublers and multipliers provide a means of stepping up the value of applied voltage without using a power transformer.

l. The regulation of voltage-multiplier systems is very poor.

47. Review Questions

a. What is the function of a rectifier?

b. What is meant by maximum peak inverse voltage?

c. Describe a gaseous electron tube.

d. What is the principal advantage of the mercury-vapor tube?

e. Describe simple half-wave rectification.

f. What is full-wave rectification?

g. Describe a bridge rectifier.

h. What are the advantages of bridge rectification?

i. What is a metallic rectifier?

j. What type of metallic rectifier is used most extensively?

k. Describe the action in a selenium rectifier.

l. Explain a simple voltage-doubler circuit.

m. Describe a voltage multiplier.

CHAPTER 3

POLYPHASE RECTIFIERS

48. Introduction

a. Polyphase prime power sources are used extensively by the armed services. These power sources are, almost without exception, 3-phase systems; military equipment designed for operation on 2-phase power is limited. For this reason, the following discussion of polyphase rectifiers treats only 3-phase systems.

b. Polyphase rectification is used in relatively large, fixed, or semifixed installations where the output power requirements run into a kilowatt or more. In many instances however, 3-phase power sources are encountered where polyphase rectification is not used. Three-phase power can be used for the 3-phase equipment or it can be separated and distributed over single-phase circuits for the operation of single-phase equipment.

c. In addition to providing large power outputs, polyphase rectifier systems are much easier to filter than single-phase systems. The power transformers must be of special construction and rugged enough to conform with particular power requirements; special 3-phase transformers often must be used rather than three single-phase units in order to avoid transformer-core saturation. In circuits using multiple secondaries, special interphase reactors are used to provide proper balance between the secondary windings. Basically, however, the filter sections for 3-phase rectifiers are the same as those used in single-phase systems except for power ratings.

d. Although polyphase rectifiers can be connected in many different circuit arrangements, only a few are of practical importance. The most commonly used are the 3-phase half-wave rectifier, the 3-phase half-wave double-Y, or 6-phase, rectifier, and the 3-phase full-wave, or bridge, rectifier. These three rectifier systems are described here.

49. Three-phase Half-wave Rectifier (fig. 28)

a. The 3-phase transformer is connected in what is called a delta-primary and a Y-secondary arrangement. These terms are derived from the schematic arrangement of the coils: The primary connections have the general configuration of the Greek letter delta, and the secondary coils are connected in the form of a **Y**. (This method of transformer connection is used in all three rectifier systems.)

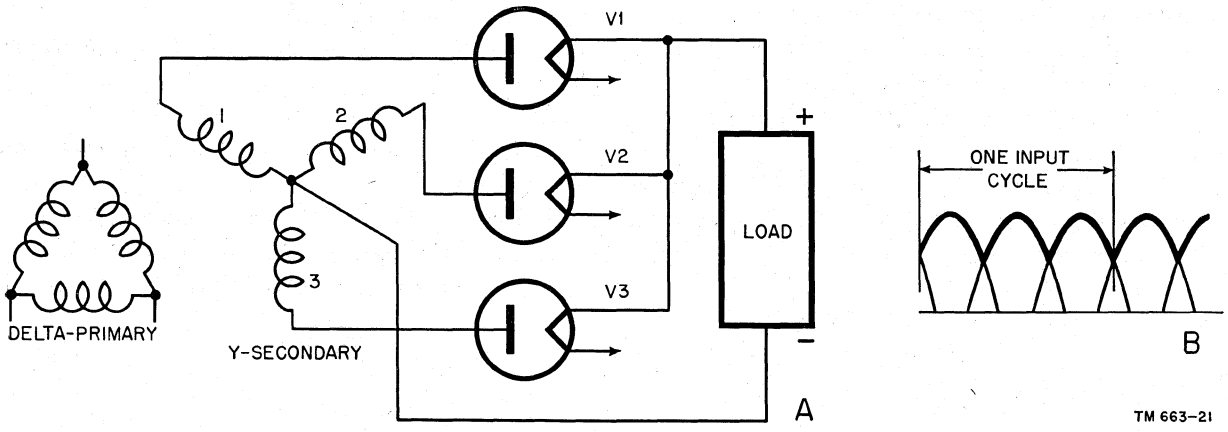


Figure 28. Three-phase half-wave rectifier circuit and output waveform.

b. Referring to A, this circuit is seen to consist, basically, of three half-wave rectifiers, with one coil, or leg, of the Y-circuit providing the supply for each rectifier tube. The cathodes of the three rectifier tubes are connected and form the positive d-c terminal. The negative terminal of the load is returned to the center point of the Y, which is common to all three secondary coils.

c. In 3-phase circuits, 1 cycle of supply voltage is considered as the combined waveform of the three individual waves appearing across each coil, each wave being displaced in time by 120°. Assume a positive alternation across coil 1 in the Y. The plate of the rectifier tube $V1$ is positive and the tube conducts. A pulse of current corresponding to the first alternation in the output waveform passes through the load. At a time 120° later, a positive alternation of input voltage occurs across coil 2 in the Y. The plate of the second rectifier tube, $V2$, now is positive and a pulse of current passes through the load. This is indicated by the second alternation in the output waveform. In the meantime, the polarity of the wave across coil 1 changes to negative and the first tube stops conducting. At a later interval of 120° a third alternation occurs across coil 3 in the Y and tube $V3$ conducts, causing a current pulse through the load, as indicated by the third pulse in the output waveform. Meanwhile, the polarity of coil 2 swings negative and $V2$ cuts off. The polarity of the voltage across the first coil now has passed through the negative half of the cycle and swings positive again, actuating $V1$. The whole operation therefore repeats itself with each cycle of the applied voltage. First one tube conducts, then 120° later the second tube conducts, and so on, with each rectifier tube passing current through the load for one-third of the time of the input cycle.

d. Examination of the d-c output waveform (B, fig. 28) shows that the pulsating component of the wave is much less for half-wave polyphase rectification than it is for full-wave single-phase rectification. From this it is apparent that less filtering is required to smooth out the fluctuations.

50. Three-phase Half-wave Double-Y Rectifier
(fig. 29)

a. As the name implies, this circuit consists, essentially, of two half-wave rectifiers of the type

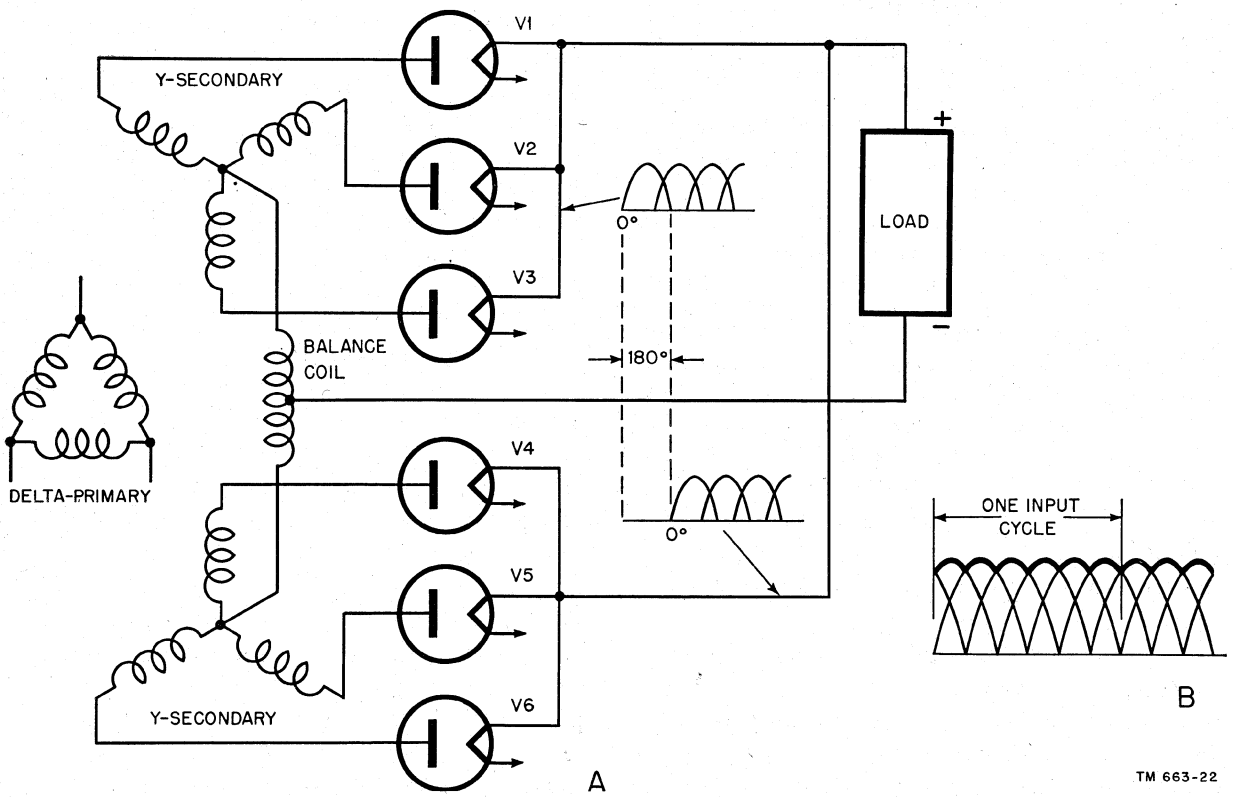


Figure 29. Three-phase half-wave double-Y rectifier circuit and output waveform

shown in figure 28 connected in parallel. The circuit uses six rectifier tubes and a special transformer circuit arrangement. Although the transformer has one delta-connected 3-phase primary, it has two 3-phase Y-connected secondaries whose coils are connected 180° out of phase with respect to each other. The center points of each of the Y-secondaries are connected through a center-tapped coil, called an *interphase reactor* or *balance* coil. The center tap on this balance coil forms the common negative return for the load.

b. In operation, the voltage polarities across the individual Y-sections are such that when the output voltage of one section is at maximum, that of the other section is at minimum. Because of the parallel connection to the balance coil, each 3-phase Y-section operates independently of the other. Consequently, as in the 3-phase half-wave rectifier discussed in the preceding paragraph, each tube carries load current for a third of the total time of a supply cycle. At any one instant, however, two tubes are delivering current to the load, but the two currents are displaced in phase. The ripple in the output waveform is small for this rectifier, having a fundamental frequency six times that of the input voltage. For this reason, it often is called a 6-phase rectifier. The output waveshape of $V1$, $V2$, and $V3$, is 180° out of phase with that of $V4$, $V5$, and $V6$. The sum of these voltages will produce the final output waveform. Compare the output waveform in B, figure 29, with that in B, figure 28.

51. Three-phase Full-wave Rectifier

a. In figure 30, 6 diodes and a conventional 3-phase power transformer are connected in a delta-primary and Y-secondary arrangement. The filaments of the diodes act as cathodes. The plate of $V1$ and the cathode of $V6$ are connected to the end of the first coil in the Y, at 1; the plate of $V2$ and the cathode of $V4$ to the second coil of the Y, at 2; the plate of $V3$ and the cathode of $V5$ to the third coil of the Y, at 3. This method of connecting the diodes to the transformer provides full-wave rectification.

b. Since the filaments of $V4$, $V5$, and $V6$ have a high potential difference between them, separate filament transformers or windings must be used for each tube. However, $V1$, $V2$, and $V3$ can be supplied with filament power from the same winding since these tubes are all at the same potential.

c. The voltages applied to each coil of the Y will be 120° out of phase with relation to each other and constantly changing in polarity. Because of this, the polarities of 1, 2, and 3 will be changing with relation to each of the others. The diodes are connected to 1, 2, and 3, and when the plates of $V1$, $V2$, and $V3$ are positive with relation to their cathodes, the tubes will conduct; when the cathodes of $V4$, $V5$, and $V6$ are negative with relation to their plates, they will conduct.

d. Assume that the alternating voltage (B, fig. 30) applied to coil 1 is approaching its peak positive value. This causes *the plate of V1 to become positive with relation to its cathode*, and the cathode of $V6$ positive with relation to its plate. At this time, point 3 is *becoming more negative in value and the cathode of V5 is negative with relation to its plate;* the plate of $V2$ at this time has a negative voltage applied to it. Since $V1$ and $V5$ are of the proper polarity to conduct, a closed circuit is provided for the current through $V5$, the load, $V1$, and coils 1 and 2 of the Y. Maximum voltage appears across the load for the period of 60° when 1 is passing through its peak positive value (B fig. 30). As the alternating voltage at 3 approaches a maximum negative value, the voltage at coil 1 steadily decreases to 0 and $V1$ no longer conducts. However, at this time, 2 is becoming positive, $V2$ conducts, and the cathode of $V5$, still being negative with relation to its plate, conducts also. The path of the current is through $V5$, the load, $V2$, and coils 2 and 3. The maximum voltage appears across the load during the period from 120° to 180° when 3 is at its peak negative value. This action continues, with maximum voltage appearing across the load during each positive and negative peak. Two diodes always are conducting in the following order: $V1$ and $V5$, $V5$ and $V2$, $V2$ and $V6$, $V6$ and $V3$, $V3$ and $V4$, and $V4$ and $V1$ (B, fig. 30).

e. Since the same results are obtained from these two rectifier systems, the selection of one rather than the other is chiefly a matter of cost or the availability of transformers fulfilling circuit requirements. In the 3-phase half-wave double-Y system, the transformer must be constructed to provide two 3-phase Y-connected high-voltage secondaries. The circuit requires a balance coil, but only a single filament transformer, or winding is needed.

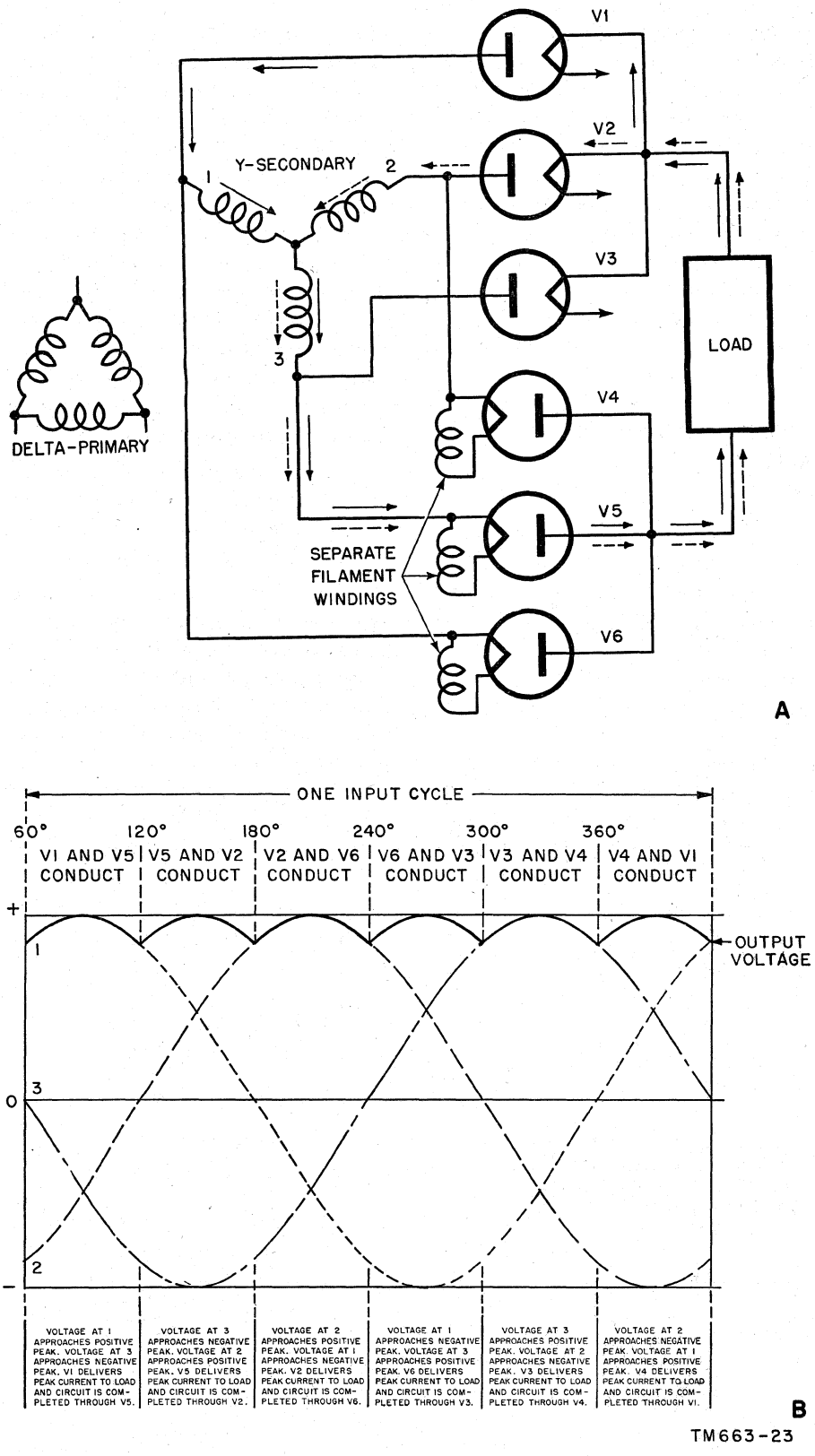

V1
V2
V3
V4
V5
V6
Y-SECONDARY
1
2
3
LOAD
DELTA-PRIMARY
SEPARATE
FILAMENT
WINDINGS
A
ONE INPUT CYCLE
60°
120°
180°
240°
300°
360°
V1 AND V5 CONDUCT
V5 AND V2 CONDUCT
V2 AND V6 CONDUCT
V6 AND V3 CONDUCT
V3 AND V4 CONDUCT
V4 AND V1 CONDUCT
+
0
−
OUTPUT VOLTAGE
VOLTAGE AT 1 APPROACHES POSITIVE PEAK. VOLTAGE AT 3 APPROACHES NEGATIVE PEAK. V1 DELIVERS PEAK CURRENT TO LOAD AND CIRCUIT IS COMPLETED THROUGH V5.
VOLTAGE AT 3 APPROACHES NEGATIVE PEAK. VOLTAGE AT 2 APPROACHES POSITIVE PEAK. V5 DELIVERS PEAK CURRENT TO LOAD AND CIRCUIT IS COMPLETED THROUGH V2.
VOLTAGE AT 2 APPROACHES POSITIVE PEAK. VOLTAGE AT 1 APPROACHES NEGATIVE PEAK. V2 DELIVERS PEAK CURRENT TO LOAD AND CIRCUIT IS COMPLETED THROUGH V6.
VOLTAGE AT 1 APPROACHES NEGATIVE PEAK. VOLTAGE AT 3 APPROACHES POSITIVE PEAK. V6 DELIVERS PEAK CURRENT TO LOAD AND CIRCUIT IS COMPLETED THROUGH V3.
VOLTAGE AT 3 APPROACHES POSITIVE PEAK. VOLTAGE AT 2 APPROACHES NEGATIVE PEAK. V3 DELIVERS PEAK CURRENT TO LOAD AND CIRCUIT IS COMPLETED THROUGH V4.
VOLTAGE AT 2 APPROACHES NEGATIVE PEAK. VOLTAGE AT 1 APPROACHES POSITIVE PEAK. V4 DELIVERS PEAK CURRENT TO LOAD AND CIRCUIT IS COMPLETED THROUGH V1.
B
TM663-23

Figure 30. Three-phase full-wave rectifier circuit and output waveform.

f. For the full-wave circuit, only one 3-phase high-voltage secondary is required, but four filament windings, or transformers, are needed to supply filament power. The cost of these additional windings, or transformers, is much less than the double-Y 3-phase transformer, and for this reason, the full-wave system will be the one encountered most frequently. Three single-phase transformers can be used in the 3-phase full-wave circuit instead of the 3-phase transformer if their ratings are sufficient to carry the maximum load current without causing saturation of the transformer cores.

52. Connecting 3-phase Power Transformers
(fig. 31)

a. Before discussing connection of power transformers to a source of 3-phase power, a brief explanation of the forms in which this power can be distributed is necessary. Three-phase power usually is distributed at higher potentials than single-phase power. For this reason, care must be taken to prevent accidents to personnel or equipment.

b. Distribution of commercial 3-phase power is divided into two categories, primary and secondary distribution. Primary distribution refers to distribution at high voltages, usually standardized at 2,300 volts. Primary distribution seldom will exceed a value of 5,000 volts. Secondary distribution refers to 3-phase voltages which have been stepped down, usually to a value of 208 to 240 volts.

c. When 3-phase power is generated locally at a fixed or semifixed installation, usually, it is 208 volts. Ordinarily, this value of voltage will not require further stepping down, since standard values of single-phase voltage for lighting and other purposes can be obtained from across a single coil in a Y-secondary. This will be explained later in this discussion.

d. Power transformers used in commercial 3-phase power systems can be connected in four different combinations, as follows:

(1) Primary in delta, secondary in delta.
(2) Primary in Y, secondary in Y.
(3) Primary in Y, secondary in delta.
(4) Primary in delta, secondary in Y.

Of these four combinations, the one used most extensively in military applications is the last one listed, primary in delta, secondary in Y. As shown in figures 28, 29, and 30, this is the only combination used in 3-phase rectifier systems. Therefore this method of connection will be the only one considered here.

e. The three primary coils of the power transformer, or transformers, if three single-phase units are used, are brought out to three insulated

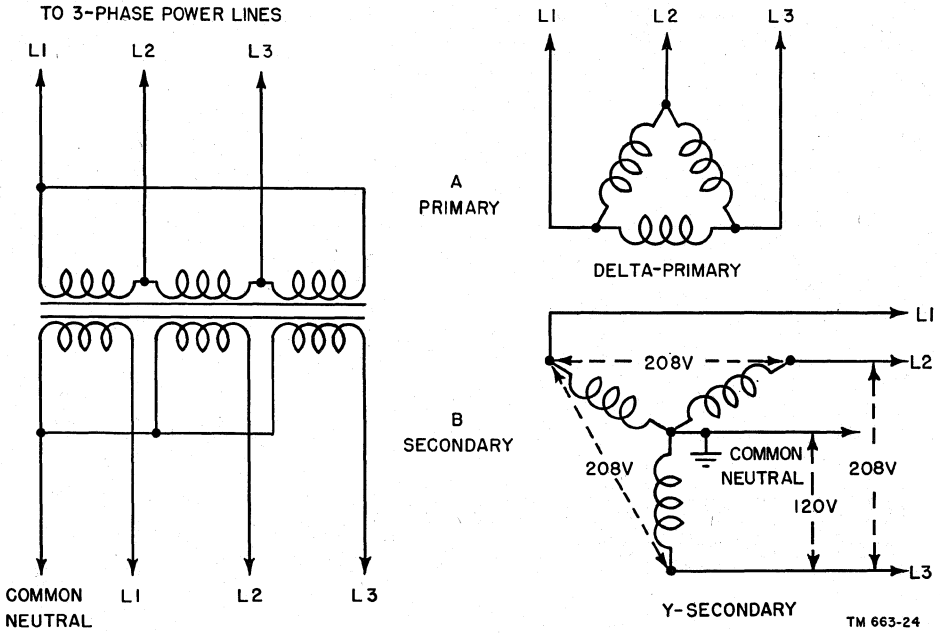


Figure 31. Connecting three-phase power transformers in delta-primary Y-secondary circuit arrangement.

terminal posts on the transformer case. The connection of these primary terminals to obtain a delta arrangement is shown in A, figure 31. It is important that each coil be connected to the other in proper phase relationship; otherwise the currents through the coils will not be balanced and damage can result to the transformer windings. In a single 3-phase power transformer, the coils usually are connected in proper phase inside the case and only the three terminals are brought out, to prevent wrong connections.

f. The connections of the secondary coils to obtain a Y-secondary with a common neutral are shown in B, figure 31. The secondary coils also must be connected in proper phase relationship to insure balanced currents in each of the legs. With the three coils properly connected, the common neutral is brought out as a separate line and, usually, is grounded.

g. The voltage existing across any *two* of the secondary lines labeled $L1$, $L2$, and $L3$ is the full secondary voltage, usually 208 volts. The voltage existing across any *one* of these lines and the common neutral line will be the voltage of a *single coil*, or *phase*, and will have a value of approximately 120 volts. Since this latter voltage is single-phase and has a *standard* value of 120 volts, it can be tapped off to supply any standard single-phase equipment. A number of single-phase equipments can be distributed across each of the lines, $L1$, $L2$, or $L3$ and the common neutral, to provide a balanced load on the transformer. At the same time, $L1$, $L2$, and $L3$ can be used together to supply power to 3-phase circuits and equipment, the limiting factor being the power output rating of the transformer(s).

53. Summary

a. While a number of different circuit arrangements are possible in polyphase rectifiers, in practical application only three are used extensively: the 3-phase half-wave rectifier, the 3-phase half-wave double-Y rectifier, and the 3-phase full-wave rectifier.

b. For 3-phase rectification, the power transformer usually is connected in delta-primary Y-secondary.

c. The output voltage from a 3-phase rectifier system is much easier to filter than that from a single-phase rectifier system. This is because the displacement between the voltage waves of each phase is 120° and overlapping occurs.

d. In the half-wave rectifier, each rectifier tube passes current for one-third of the time of the input cycle.

e. The 3-phase half-wave double-Y circuit requires two sets of secondary windings, each of which is connected to the ends of a center-tapped balance coil.

f. The output of the double-Y circuit is a wave pulsating at six times the frequency of the input wave.

g. The 3-phase full-wave rectifier uses a single set of secondary windings to produce the same output as the double-Y circuit. However, three additional filament windings are required for three of the six tubes used.

h. Three-phase rectifier systems are used only where large amounts of power are required, usually in kilowatts.

54. Review Questions

a. Where is polyphase rectification used?

b. The usual polyphase power system consists of how many phases?

c. How many polyphase rectifier circuits commonly are used? Name them.

d. In the 3-phase half-wave system, for what interval of time does each tube conduct?

e. Describe the 3-phase half-wave double-Y rectifier circuit.

f. What is the function of the balance coil?

g. In the double-Y circuit, how many tubes are conducting at a time?

h. What is the pulsating frequency of the output wave in the double-Y system?

i. Why does the full-wave rectifier circuit require additional filament windings?

j. Since the output waveform of the half-wave double-Y rectifier is the same as the full-wave system, what is the prime factor in selecting one circuit over the other?

k. Describe what is meant by delta-primary Y-secondary.

CHAPTER 4

FILTER CIRCUITS

55. General

a. WHY A FILTER IS REQUIRED. From the discussion of single-phase and polyphase rectifiers in chapters 2 and 3, respectively, it is evident that the output of a rectifier is not a simple direct current. An examination of the various rectified output waveforms reveals a fluctuating or pulsating current unlike the smooth, even, direct current required for the operation of most electronic circuits. The pulsating waveforms for both half-wave and full-wave rectification of single-phase and triple-phase voltages are shown in figure 32. The extreme example of this pulsating d-c is shown in B by the output of a single-phase, half-wave rectifier. In contrast with this violently fluctuating current is the smooth, even output waveform of the battery in A. While the pulsations existing in the waveforms of C, D, and E are progressively smaller, these rectified voltages still are unsuitable for most applications. Consequently, the output from a rectifier must be modified to approach, as nearly as possible, the steady state of the battery voltage. To accomplish this, the fluctuations in the rectified pulses must be smoothed out by a process called *filtering*.

b. BASIC PARTS OF FILTER CIRCUIT. Filtering is accomplished by means of capacitors, inductors, and resistors. The inductors commonly are referred to as *filter chokes*, *chokes*, or *choke coils*. These components can be connnected in many different circuit arrangements, three varieties of which are fundamental. These are shown in A, B, and C, figure 33. The choke L and the resistor R

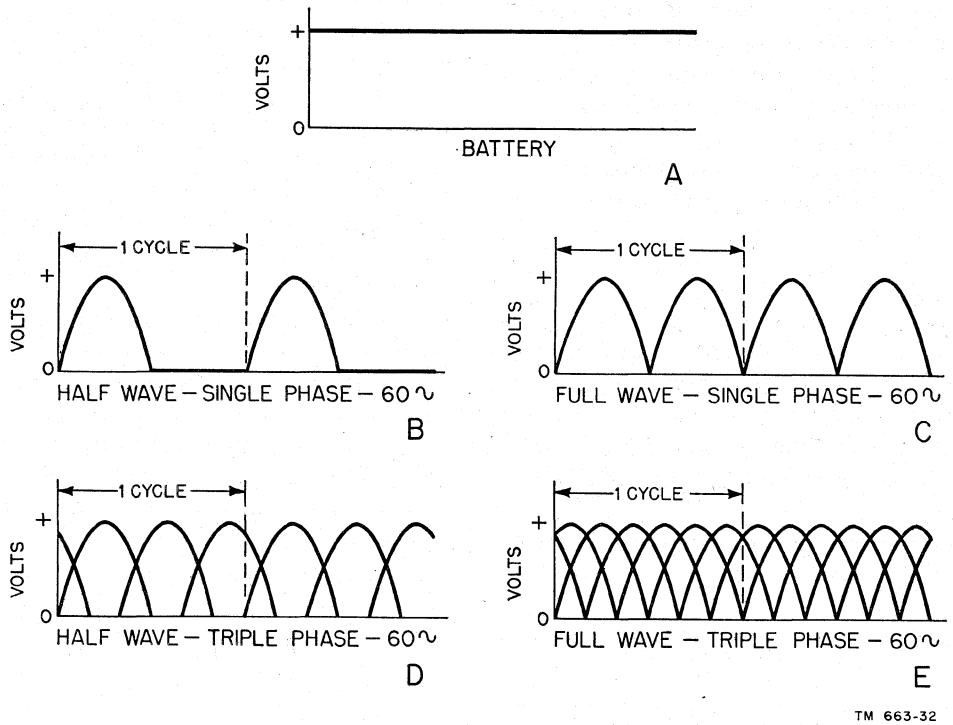
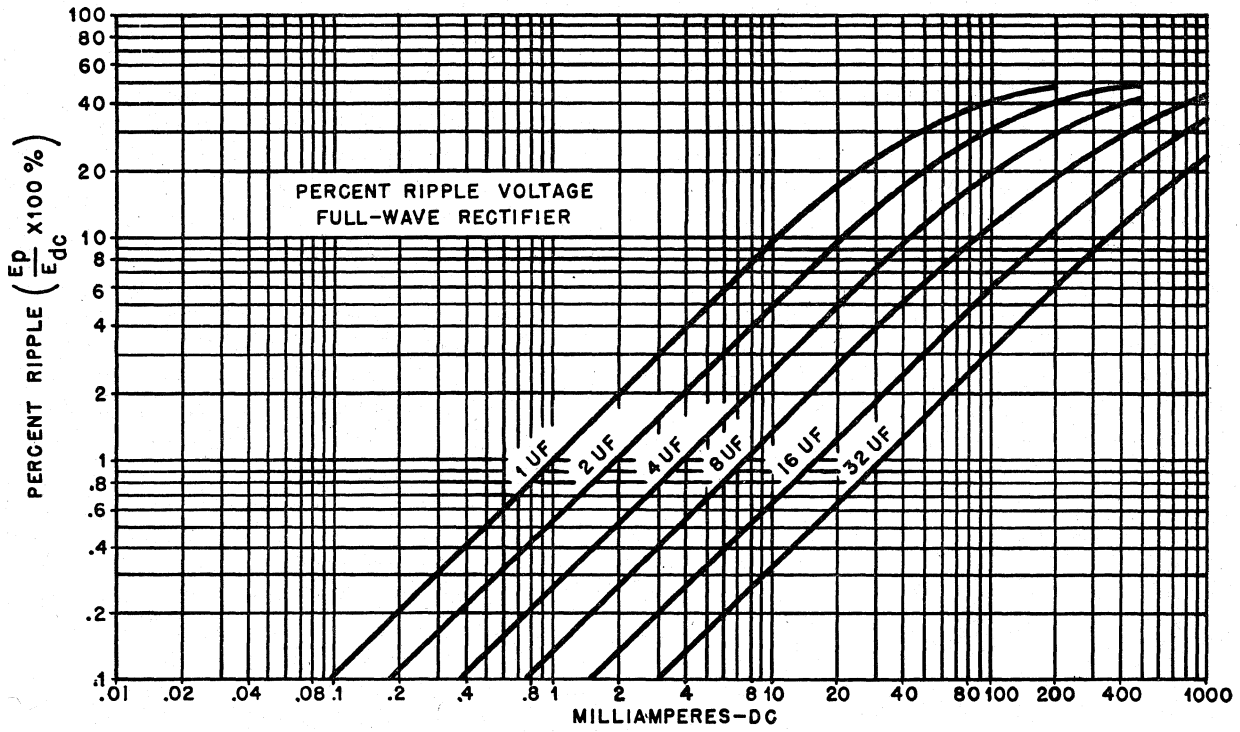


Figure 32. Comparison of various rectified voltages with steady voltage obtained from a battery.



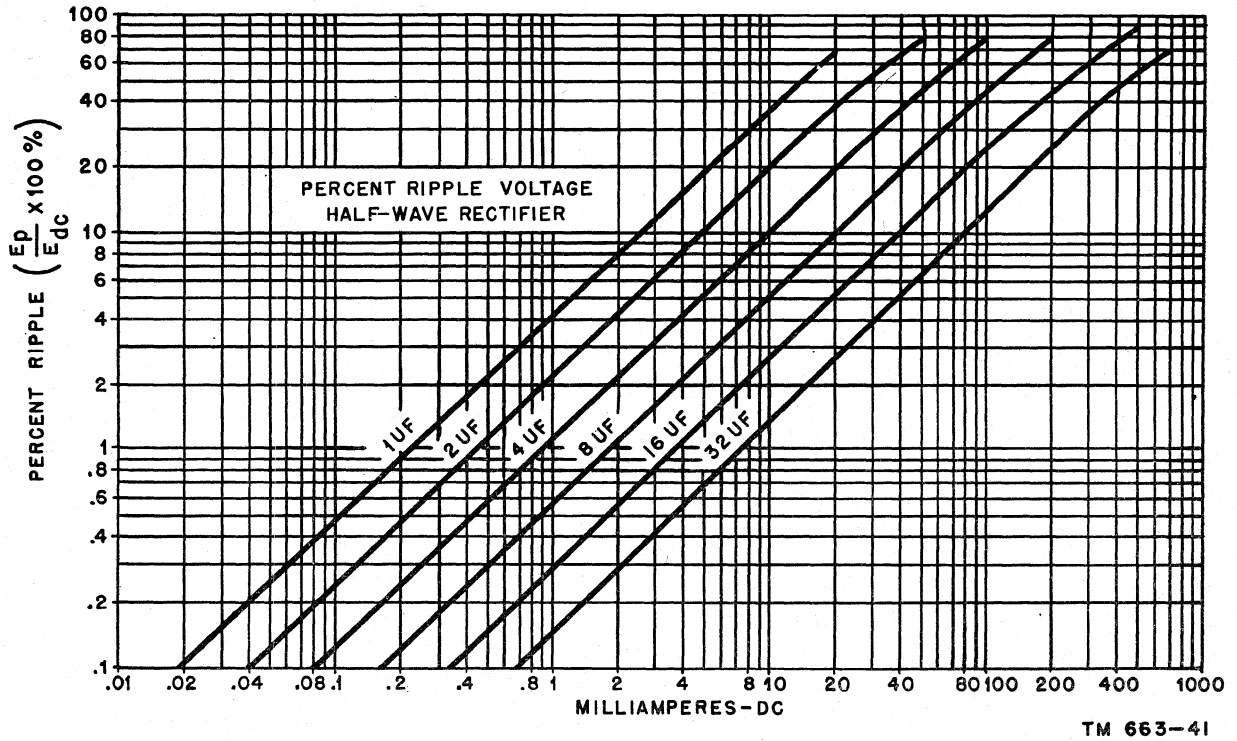


Figure 37. Percentage of ripple compared with various values of input capacitance and current drain for half-wave and full-wave rectifiers.

is opened and closed and sharp pulses of current occur, the current attempts to change almost instantaneously and the inductive effect is large. In other words, inductance tends to hold back the current when it rises in value and to keep it flowing when it decreases.

b. A, figure 38, shows an inductor, L, in series with a load resistor, R, and connected across the output of a full-wave rectifier tube. In B, the light-line pulses, extending from O on the base line to peak E, represent the pulsating output from the rectifier tube. The superimposed heavy wavy line represents the output current after these rectified pulses have passed through choke coil L. The action is described in *c* below.

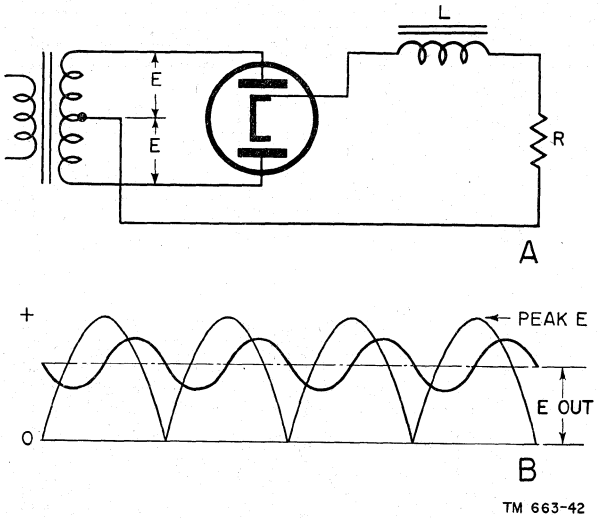


Figure 38. Full-wave rectifier with single inductance filter in series with circuit and associated waveforms.

c. When the rectified pulse from the tube is applied to L, the rapidly rising current in the pulse is choked back by the inductance effect of the coil. This is shown by the first half-cycle of the heavy current line of B, figure 38. As the rectified pulse reaches its peak, the rate of change slows down, the choking action lessens, and the current through L begins to rise. Passing through the peak, the rectified pulse begins to decline, but the inductance characteristic of the choke in counteracting any current change tends to keep the current flowing in the circuit. This is indicated in B by the rise in the heavy line as the rectified pulse falls off. The current through the choke continues to rise until the rectified pulse approaches O. At this point, there is not enough energy in the circuit to maintain the value of the current, and it falls off as indicated by the heavy line. An instant later the next pulse begins, the inductive force reverses, retarding the rise of the current pulse, and the current through the coil continues to fall off as before. When the rectified pulse nears its peak, the rate of current change decreases and once again the current through the circuit begins to rise. This action repeats itself as long as the rectified pulses are applied to the choke coil L. The result is a fluctuating current through the circuit which is indicated by the heavy line superimposed on the rectified current pulses shown in B. The average value of the output voltage is represented by the dashed line passing through the O axis of the heavy wavy line and indicated as E out.

d. From this description of an inductance filter, a number of related conditions are apparent. The first is that the choke coil tends to maintain a flow of current through the rectifier circuit at all times. Also, it prevents the sharp rise of current that would occur if the input filter element were a capacitor instead of an inductor. Consistent with the absence of these peak pulses, it is obvious that the output voltage never can reach the peak value of the applied input voltage, as with a capacitor input filter. The output voltage available from a power supply using a choke-input filter circuit is much less than that obtained with a capacitor input, and since abrupt peak currents are absent with this type of filter input, the power-supply regulation is much improved. Inductance-input filters are used in the filter circuits of rectifier tubes, which cannot withstand sudden current surges.

e. The choke decreases the ratio of peak-to-average current and prevents the d-c output voltage from rising above the average value of ac applied to the rectifier (B, fig. 38). Both the output voltage and the peak plate current depend on the inductance of the choke and the resistance of the load. The minimum inductance needed to keep the output voltage from rising above the average rectified a-c is called the critical inductance. This value of inductance for a 120-cycle rectified voltage can be determined approximately by use of the following equation:

$$L_c = \frac{R_o}{1000}.$$

If the inductance of the choke is less than its critical value the circuit operates as a capacitor input

filter. An increase in inductance to more than the critical value will decrease the ratio of peak-to-average plate current and maintain a more uniform current flow through the inductor. Increasing the value of inductance beyond a certain point shows little improvement in performance and the *optimum value* of inductance is equal to twice the critical inductance. The value of inductance required varies directly with the effective load resistance as indicated in the formula above. Since the inductance of any choke varies inversely with the d-c flowing through it, an increase in the effective load resistance causes the ratio of peak-to-average current to decrease. The *swinging choke* is designed to have a *critical value* of inductance at full load and an *optimum value* at no load. This maintains the peak-to-average current ratio within the prescribed limits over a wide range of changing load currents and results in improved regulation.

58. Inductance-Capacitance Filter

a. The discussion of capacitance and inductance in a filter circuit shows that the final result of the filter action is the maintenance of current flow through the rectifier circuit. However, the output from a single capacitor or inductor still is fluctuating too much for most applications. The combined use of two or more of these elements in a filter circuit would eliminate these pulsations, or reduce them to a minimum, and this is exactly what is done in the filter circuits of conventional power supplies.

b. A basic filter circuit illustrating the use of capacitance and inductance is shown in A, figure 39. The circuit uses an input capacitor, $C1$, an inductor, L, in series with the circuit, and another capacitor, $C2$, connected in shunt with load resistor R. This circuit arrangement is called a π filter. The output waveforms occurring across the capacitors for full-wave rectification are shown in B and C.

c. The charging and discharging action of input capacitor $C1$, as previously explained, produces the fluctuating waveform shown in B. Inductor L adds further smoothing action by resisting any sudden changes caused by the rise and fall of the current pulsations. The current applied to capacitor $C2$ after passing through L is, therefore, more constant than that occurring across $C1$. However, the small remaining fluctuations cause

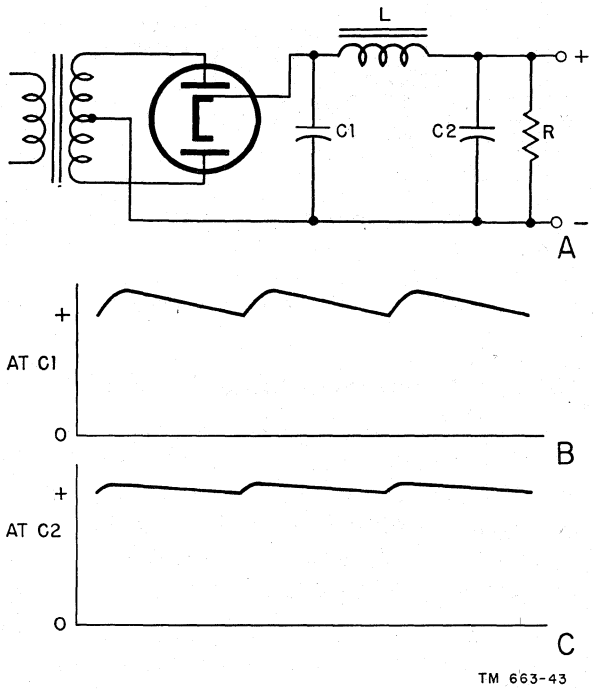


Figure 39. Full-wave rectifier using simple π filter circuit and associated waveforms.

$C2$ to charge and discharge in the same manner as $C1$. The final result is to produce the relatively smooth waveform shown in C.

d. By using another L-filter section, these small fluctuations can be reduced still further. Additional filter sections can be added until the fluctuations represent but a small fraction of the power-supply output voltage. The number of sections to be added to the filter circuit depends on the nature of the equipment being supplied. Some electronic equipment requires a high degree of filtering, and other equipment is not so critical in this respect. When fluctuations must be held to a rigid minimum, voltage stabilizers and regulators are connected into the power-supply circuit.

e. A full-wave rectifier using a choke input in what is called a double-L-filter system is shown in figure 40. In the L filter, the charge and discharge of $C1$ are much less than before because the limiting action of $L1$ tends to keep the current constant and $L2$ and $C2$ provide additional filtering. Additional L-filter sections can be added to the basic circuit shown here in conformance with the requirements of the power-supply output. When both good regulation and filtering are required, choke input filtering is used, $L1$ is a swinging choke and $L2$ is a smoothing choke.

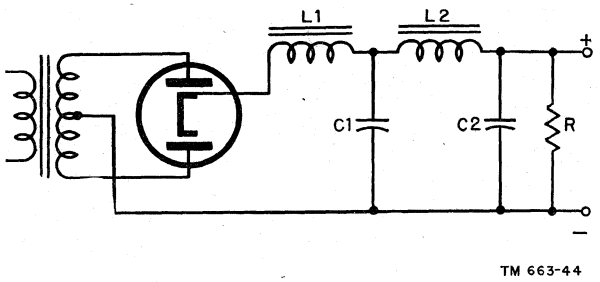


Figure 40. Full-wave rectifier using choke input in double-L-filter circuit.

59. Resistance-Capacitance Filter

a. Sometimes resistors are substituted for inductors in filter circuits. This is illustrated in figure 41, which shows a resistor replacing the choke in a simple π filter arrangement. Although the resistor affords some filtering action, it is not as effective as a choke coil.

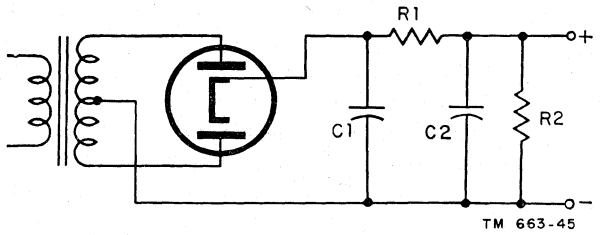


Figure 41. Resistor used in place of choke in simple π filter in full-wave rectifier circuit.

b. The action of $C1$ in this circuit is the same as in the capacitor-choke arrangement previously described. By charging and discharging into the line, it provides a certain amount of filtering. This filtering is increased if the value of $C1$ is increased. Better performance is obtained, however, if the added capacitance is in the form of a separate capacitor $C2$, connected in series with a resistor $R1$ in the π filter circuit (fig. 41). The improved filter action results from the relative reactances of capacitors $C1$, $C2$, and load resistor $R2$. The pulsating current from the rectifier can be considered as having two parts—an a-c component which is represented by the pulsations and a d-c component which is the steady average value of the output current. Because the pulsations occur at the power-line frequency of the input voltage, or some multiple thereof, the values of $C1$ and $C2$ are so chosen that their reactances are very low for these frequencies. Both the a-c and d-c components of the rectified current flow through series resistor $R1$; therefore, a voltage drop, depending on the value of resistance and the magnitudes of these two currents, occurs across $R1$. When the pulsating direct current leaves $R1$, two parallel paths consisting of $C2$ and $R2$ are presented to it. The separation of the a-c and d-c components occurring at this point depends on the relative reactance and resistance of $C2$ and $R2$. The reactance of $C2$ being small at the frequency of pulsation, most of the a-c component is bypassed by the capacitor. The d-c component flows through $R2$. The charging and discharging of $C2$ by the pulsating component smooths out the fluctuations and a relatively pure direct current is delivered to the load.

c. The filtering action obtained in this manner is not the best possible, and the use of additional filter resistors is limited by the output current requirements. Since these resistors are connected in series with the power-supply circuit, the output current must flow through them and, unless this current is small, appreciable voltage drops occur across the filter resistors. The reduced output voltage resulting from these voltage drops makes the circuit impractical for most applications requiring even a moderate amount of current. This type of filter, therefore, is limited to applications in which the current drain is small, making the voltage drops across the resistors negligible. An example of the use of resistor-capacitor filters is in the high-voltage power supplies of cathode-ray tubes, where high voltage and low current are required.

60. Effect of Input Frequency

a. The frequency of the a-c input voltage to a rectifier system is a determining factor in the design and construction of the power supply. Most low-power and medium-size units are designed for operation from a-c power lines at a frequency of 60 cps. The rectified pulses from a single-phase, half-wave rectifier have this frequency, since only one alternation of each input cycle is rectified. In a single-phase, full-wave rectifier, the rectified pulses are twice the input frequency, because both alternations of the input cycle are rectified. For 3-phase, half-wave rectification, the rectified pulses are three times the input frequency, and for 3-phase, double-Y, full-wave rectification, the pulses are six times the frequency of the input voltage.

b. It was shown in filtering the output of a

are in series with the load in these circuits and capacitors C, C1, and C2 are across the load. A capacitor sometimes is connected across the choke in the series arm to form a tuned circuit, making the filtering action more effective. In radio receivers using electrodynamic speakers, the field coil of the speaker often is used as the filter inductor. The coil then performs two functions simultaneously: It is energized to provide the magnetic field for the speaker, and at the same time it serves in filtering the output of the rectifier. Often another L filter is added to the basic π filter shown in A, figure 33. In this arrangement, two chokes are in the series arm of the circuit and three capacitors are connected in shunt. The circuit shown in C commonly is called a choke-input filter; the circuits in A and B are known as capacitor-input filters. Modifications of these three basic circuit arrangements consist, in the main, of additional capacitors, choke coils, or resistors.

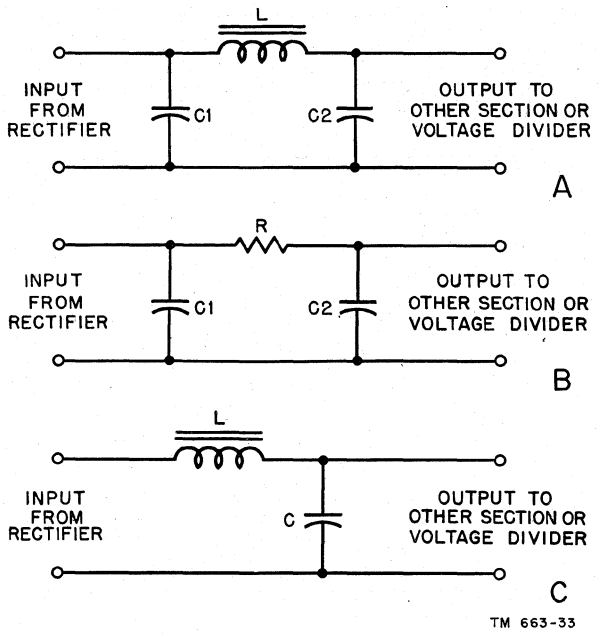


Figure 33. Basic filter circuits.

c. Ripple Component.

(1) The unfiltered output of a rectifier can be considered the resultant of an alternating current superimposed on a direct current. The alternating component of the rectified voltage commonly is called *ripple.* The frequency components of the ripple and their respective magnitudes are the prime factors in determining the degree of necessary filtering. Two other factors, however, must be considered—the over-all regulation of the power supply and the amount of residual ripple that can be tolerated in the equipment being supplied with power. The effectiveness of the filter circuit is determined from the ratio of the rms value of the ripple voltage to the d-c value of the output voltage. This ratio is expressed as percentage of ripple:

$$\text{Percentage of ripple} = \frac{E_r \times 100}{E_{dc}}\%.$$

(2) B, C, D, and E of figure 32 show that the frequency of pulsation, or ripple frequency, is different for each waveshape of the four basic rectifiers. The half-wave pulsations in B are at the fundamental frequency of the applied a-c voltage, which is 60 cps. The full-wave pulsations in C contain the second harmonic of the fundamental, but no fundamental frequency. This is apparent since both alternations of the fundamental input cycle are rectified. The half-wave, 3-phase waveform in D contains the third harmonic, but has no fundamental or second-harmonic content. The full-wave, 3-phase waveform in E contains the sixth harmonic, all frequencies below the sixth harmonic being absent. As the ripple frequency increases, ripple magnitude decreases and becomes easier to filter.

d. Brief Description of Filter Circuit.

(1) Assume that the output of a half-wave rectifier (B, fig. 32) is applied to the filter circuit shown in A, figure 33 and a load is placed across the output. When the first half-wave pulse appears across capacitor $C1$, current flows through the circuit and the capacitor charges to the peak value of the pulse. During the half-cycle when the rectifier is not conducting $C1$ discharges into the line through choke L. On the next alternation when current flows through the circuit, $C1$ again charges to peak value. When the current flow is cut off on the next half-cycle, $C1$ returns some of its charge to the line. Although no current

is delivered from the rectifier to the filter circuit on alternate half-cycles, a current caused by the charging and discharging of capacitor $C1$ flows through the circuit during these intervals. In this manner, the gaps in the waveform in A, figure 32 are partly filled in and a more uniform current flows in the output circuit.

(2) Although the output current has been made more uniform by the action of $C1$, it is still far from the smooth d-c required, and L and $C2$ provide additional filtering action. An inductor functions to retard or restrict any *change* in the current flowing through it. Consequently, when the rectified current pulse is applied to choke L, it immediately tends to retard or limit the current through it. The effect is to choke back or flatten the peaks of the rectified pulse, which gives it the name *choke* coil. The action of $C1$ filling in the gaps and the action of choke L restricting the peaks of the rectified half-wave pulse result in a fairly steady flow of current through the output circuit. Because of the charging and discharging action of $C1$ and the retarding action of L, the current applied to $C2$ is flowing steadily; however, it still contains pulsations that are too high in amplitude for most applications. By charging and discharging on these pulsations in exactly the same manner as $C1$, capacitor $C2$ further filters the output, often to the degree where it is usable for ordinary applications. By connecting additional capacitors and chokes in the basic circuit, further filtering action is obtained, resulting in the pure d-c required in the output of the power supply. Resistor R in B, figure 33 is substituted for the choke coil in cases where restrictions on cost or space make use of the inductor inadvisable, or where a lesser degree of filtering can be tolerated. Although a certain amount of filtering is obtained with resistor R at low power-line frequencies, the efficiency of a resistor as a filtering device is much less than that of an inductor. The following paragraphs describe in detail the filtering action accomplished by each of these basic components.

56. Capacitance Filter

a. As previously described in the discussions on rectifiers (chs. 2 and 3), if a load resistor is connected across the output of the rectifier, current pulses flow through the resistor each time the rectifier conducts (fig. 34). The direction of current flow through resistor R and the polarity of the potential existing across R are shown in A. The waveforms in B and C represent the unfiltered output from a half-wave and a full-wave rectifier, respectively. Note that the dashed line indicating the average value of output voltage for the half-wave rectifier has less than half the amplitude of

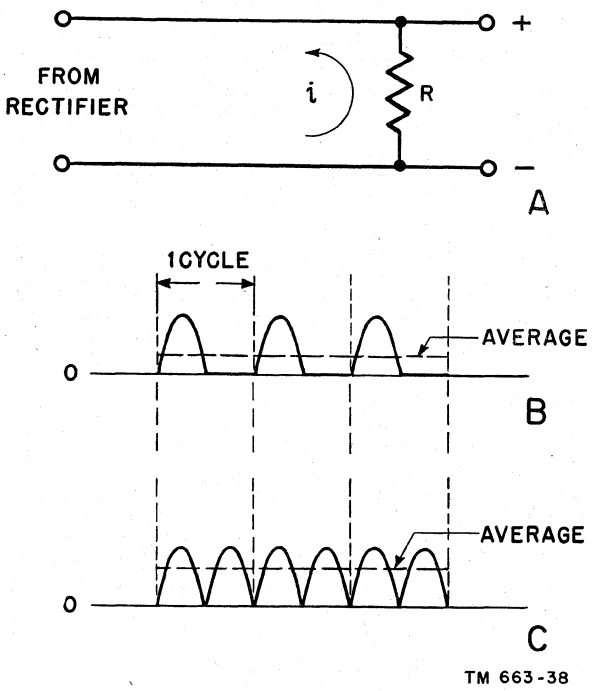


Figure 34. Rectified half-wave and full-wave pulses occurring across a load resistor in an unfiltered circuit.

the peaks. In the full-wave rectifier waveform in C, this average value is greater than half, but still much less than the peak amplitude of the waveform. Obviously, the voltage pulses occurring across the load resistor must be filtered before the voltage is usable. When a filter capacitor of the proper value is connected across the output of the rectifier, the output pulses will not only be filtered but their average value will be increased also.

b. A, figure 35, shows a single-capacitor filter connected across the rectifier tube and in shunt with the load, R. The value of this capacitor

must be large in order to present a small reactance to the pulsating rectified current and to store sufficient energy when charged. The ohmic value of load resistor R is much greater than the reactance of C. Therefore, when a pulse is delivered by the rectifier, most of the current takes the path of least opposition offered by capacitor C. The result of this action is to charge C to a value which approximates the peak value of the input voltage, E, being less than this value by the voltage drop across the rectifier tube. This charge is indicated by the heavy line on the waveform in B, figure 35,

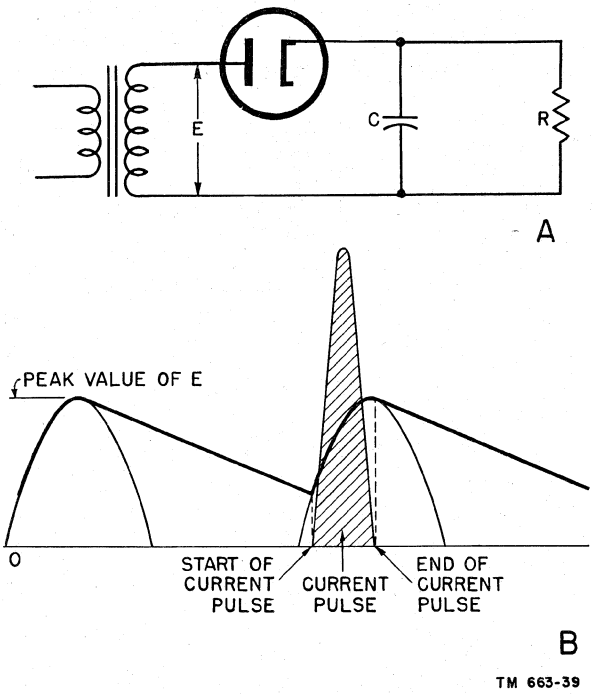


Figure 35. Half-wave rectifier circuit with a single capacitor connected in shunt with the load and associated waveforms.

the peak value being indicated at the top of the pulse.

c. On the next half-cycle of applied voltage, the plate is negative and no current flows through the tube. During this interval, capacitor C discharges into the line. Since the rectifier tube is cut off and no current can flow in this direction, the filter capacitor discharges through load resistor R. This discharge is shown by the heavy line which slopes downward to the right of the peak value of the charge in B, figure 35. Although the rectified current pulse from the rectifier rises and falls abruptly to zero, the voltage which capacitor C restores to the circuit during the cut-off time of the tube shows a gradual decline which never reaches zero. As the charge leaks off the capacitor, the extent of the decline is determined by the magnitude of the current drain through load R and the capacitance of C. For any given current drain, the value of C determines the rate of decline of the discharge voltage; the larger the value of C, the less the rate of decline and the greater the output voltage existing across the load. Conversely, the smaller the current drain or the larger the R between charging pulses, the smaller is the decrease in output voltage. This means that if R or C is increased the ripple component will decrease.

d. Assuming established values of capacitor C and load resistor R, the filter capacitor continues to discharge until the next positive current pulse occurs. In B, figure 35, a substantial charge still remains on C when the next pulse comes along. This means that the rectified pulse of current cannot start to flow until the voltage, E, exceeds the existing charge on capacitor C. The higher the value of the charge remaining on C, the later will be the *start* of the pulse of current delivered by the rectifier. When the voltage, E, reaches a value exceeding that of the charge on C, current starts to flow and again the capacitor is charged. Because of the existing charge on C, the time required to charge C to the peak value of E is much less than for the first pulse. Shortly after the charge has reached peak value, the tube stops conducting, since the fall in the input voltage, E, is much more rapid than the rate of discharge of C, and the cathode soon becomes positive with respect to the plate of the tube. After the first few cycles of operation, the current pulses which constitute the charging current occur as sharp pulses. The slower the rate of discharge of the filter capacitor, the shorter is the time duration of the charging current pulses. This current pulse is shown cross-hatched in B, figure 35, and indicates that the sharper the current pulse, the greater is the instantaneous value of charging current. The amplitude of the pulse shown is arbitrary and does not indicate any relative value.

e. Examination of the heavy line in the waveform of B, figure 35, shows that capacitor C stores energy when the tube is conducting and maintains current flow through the output circuit when the tube is cut off. The gaps existing in the waveform of the half-wave rectifier output are filled in. The output is still pulsating, however, owing to the

falling off in voltage during the discharge period, and depressions remain, even though they are much smaller. If the value of C is increased, the slope of the voltage discharge curve or ripple current is much less. There is a limit, however, to the value to which capacitor C can be increased, and that is the magnitude of the current pulse at the starting instant of the charging process as shown in B. Rectifier tubes bear peak-current ratings. These ratings can be exceeded if the value of C becomes too large, causing a break-down in the tube. Therefore, a compromise must be established which involves the optimum value of C, the permissible peak value of the charging current, and the current drain by the lead.

f. The fact that a large charging current is present with this input capacitor precludes the use of capacitor-input filters with mercury-vapor rectifier tubes. Since these tubes cannot withstand large surges of current, excessive charging current passing through the tubes will destroy them. Another disadvantage of capacitor input filters is poor regulation, because the rate of decline of the charging voltage is a direct function of the current drain through the load; the greater the current drain, the more rapid the fall of output voltage.

g. When the filter capacitor C is connected across the output of a full-wave rectifier (A, fig. 36), the basic effect is the same. The time for decline of the discharge voltage is cut in half, since full-wave rectification provides two current charging pulses where only one existed in the half-wave system. This means that with the same value of input voltage (represented by $E1+$ or $E2$ in A, fig. 36), the following advantages over the half-wave system are realized: A higher average value of output voltage is available from the filter circuit; a reduced swing or fluctuation exists for any one value of current drain required by the load; a higher rate of variation in the output current can be tolerated. These conditions are evident from an examination of the heavy line in B. Although the rate of decline of the discharging curve is much less than with half-wave rectification, pulsations still exist in the waveform, and additional filtering is needed to provide the required d-c output.

h. Summarizing, the pulsations existing across capacitor C and load resistor R represent a form of distortion. Although they consist of a fundamental frequency, numerous other frequency components are present, resulting in extremely undesirable hum in the output. Therefore, it is necessary to use additional filter elements in conjunction with capacitor C to attain the desired result. In figure 37, curves are given for percentage of ripple for various values of capacitor-input filter with single-phase, half-wave, and full-wave rectifiers. For a given current drain, the percentage of ripple for various values of capacitance can be determined. In the curves for the half-wave rectifier, for example, if a 4-μf capacitor is used as a filter and the current drain is 100 ma (milliamperes), the ripple voltage is 80 percent. With the same current drain and a 16-μf capacitor, the ripple voltage is 24 percent. If the same current

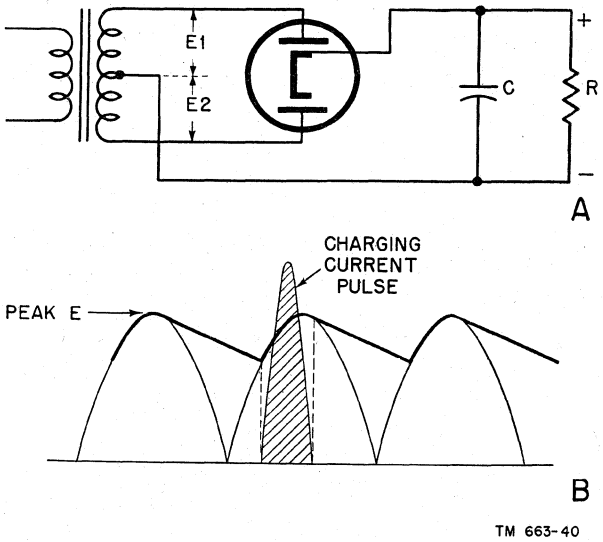


Figure 36. Full-wave rectifier circuit with single capacitor across output and associated wave forms.

(100 ma) is taken from the full-wave rectifier, a 4-μf capacitor allows 20 percent ripple, and a 16-μf capacitor allows only 6 percent ripple.

57. Inductance Filter

a. The ability of a choke coil to function as a filter element in a power supply depends on its basic property, inductance. This can be defined as the property of a coil that tends to oppose a *change* in the value of a current flowing through it. Inductance is represented by the symbol L, and its unit of measurement is the *henry*. The effect of inductance in a circuit is evident only when the current is changing and the value of the inductance varies directly with the speed of the changing current. For example, when a switch

full-wave rectifier (fig. 36), that the decline of the discharge voltage across the input capacitor becomes less as the frequency of the rectified pulses increases. It is evident that half-wave rectification, which provides only one rectified pulse per input cycle, requires more extensive filtering than do other 60-cps power supplies. It then follows that the rectified output from the polyphase systems, which is pulsating at six times the input frequency, is the easiest to filter of all the 60-cps power supplies discussed here.

c. As the frequency of the a-c input is *increased*, the reactance of a capacitor decreases and the reactance of a coil increases. This increases the filtering effectiveness of these components, so that smaller and lighter units can be used to produce the same degree of filtering as at lower frequencies. Also, transformers of the same turns ratio and power rating are smaller in size and lighter in weight as the input frequency is increased. These factors are of great importance in electronic equipment designed for use in aircraft or in similar installations where space and weight restrictions exist. In these applications, primary power sources are designed to deliver the required power-supply input voltages at a number of frequencies up to 1,000 cps.

61. Summary

a. A filter is required to smooth the pulsations present in the current pulses delivered by the rectifier.

b. Filtering is accomplished by means of capacitors, inductors, and resistors connected in various circuit arrangements.

c. The charging and discharging of capacitors in filter circuits with the rectified current pulses tend to keep current flowing and at the same time provide a high value of output voltage.

d. A disadvantage of capacitance-input filters is poor regulation of the power-supply voltage.

e. By opposing any change in the existing current flowing in the circuit, an inductor tends to keep the current flowing at a constant rate.

f. The output voltage from a choke-input filter is lower than that from a capacitor-input filter, but better output voltage regulation is obtained.

g. Chokes are connected in series with the line; capacitors are connected in parallel.

h. Sharp current pulses are present at the rectifier output with capacitor-input filters.

i. Sometimes, resistors are used with capacitors as filter components; at times in place of, or in conjunction with, choke coils.

j. A simple π filter consists of a series choke or resistor with a capacitor shunted across each end. One or more π filter sections can be used in a filter system.

k. As the frequency of the input voltage to the power supply is increased, filtering becomes easier and smaller components can be used.

l. Power supplies for aircraft radio and radar are operated at higher than power-line frequencies. The component parts are much smaller and lighter than conventional parts.

m. An increase in L, R, or C will decrease the ripple component in any filter circuit.

n. A swinging choke is used as an input choke and improves the regulation of the power supply.

62. Review Questions

a. Why is a filter used?

b. What are the basic parts of a filter circuit?

c. Describe a basic filter circuit.

d. What is the function of the input capacitor in a capacitance-input filter?

e. Name one advantage of the capacitance-input filter. Name one disadvantage.

f. Describe the action of the choke.

g. Name one advantage of the choke-input filter.

h. Name the factors limiting the size of the input capacitor.

i. What is a π filter? An L filter?

j. When are resistors used as filter elements?

k. Name some disadvantages in the use of resistors. Advantages.

l. How does increased frequency of input voltage affect the filter circuit?

CHAPTER 5

VOLTAGE DIVIDERS

63. General

a. Usually, a voltage divider is a resistor, or a series of resistors, connected in the output of the power supply and tapped at a number of points along its length to provide a selection of different values of output voltage. A voltage divider is required in any power supply designed to deliver power to a load having a variety of voltage and current requirements. In the preceding discussions on rectifiers and filter systems, the load was shown for purposes of illustration as a resistor connected across the output of the power supply. Although the load is indicated in this manner, the resistor load symbol must not be confused with the actual load, which is the equipment being supplied with d-c power.

b. The voltage divider, when connected *across* the power-supply output, also acts as a *bleeder* resistor. Charges remaining on the filter capacitors when the power supply is turned off discharge or bleed off through the voltage divider and shock hazard is eliminated. The voltage divider also serves as a fixed load on the power supply. No matter what other equipment is connected to the power supply, the divider draws a fixed current from the filter system as long as the rectifier is operating. The value of this current is usually 10 to 15 percent of the total current available. The bleeder tends to stabilize the output voltage, providing better regulation.

c. The current flowing through the voltage divider and the value of resistance between taps determine the division of voltages along the divider. Therefore, any change in the load current drawn from any particular tap affects the voltage distribution of the entire voltage-dividing system. The maximum amount of current drawn from the divider must be within the limits prescribed by the wattage rating of the voltage divider. When individual resistors are used, the wattage represents the product of the voltage existing across each component and the total current flowing through it. Where a single tapped resistor is used, the wattage rating is computed for each section on the basis of Ohm's law, and the section having the maximum value of E times I will determine the wattage of the entire divider. To prolong the life of the voltage divider and maintain the desired efficiency, resistors having double the indicated wattage rating are used. This must be borne in mind when replacing defective components.

64. Simple Two-Circuit Voltage Divider (fig. 42)

a. The total output voltage available from the power supply illustrated is 250 volts. The maximum output current is 70 ma. Capacitor $C1$ is the final filtering element in the filter circuit. Capacitor $C2$, usually of lower value, provides extra filtering across resistor $R2$.

b. Circuit A requires the full 250 volts and draws 40 ma of current. Circuit B requires only

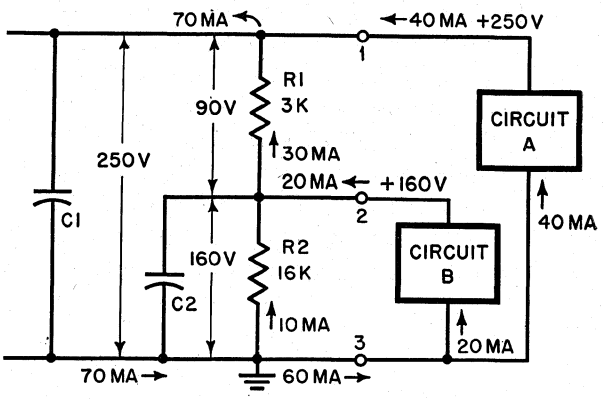


Figure 42. Simple voltage-divider circuit connected across output of filter circuit and supplying two circuits, A and B.

160 volts for operation and draws 20 ma of current. Consequently, 60 ma of the total available current is drawn by these two load circuits, leaving a remainder of 10 ma which represents the bleeder current. This steady bleeder current flows through both sections of the divided as long as circuits *A* and *B* are drawing their rated currents.

c. Since only 10 ma is to flow through *R*2 and the voltage required at 2 is 160 volts, the value of *R*2 will be

$$R2=E/I=\frac{160}{0.01}=16{,}000 \text{ ohms.}$$

The voltage across *R*1 then must be

$$RT-R2=250-160=90 \text{ volts.}$$

The current through *R*1

$$IR2+IB=0.01+0.02=0.03 \text{ ampere}$$

and the resistance of *R*1

$$R1=E/I=\frac{90}{0.03} \text{ or } 3{,}000 \text{ ohms.}$$

The total resistance of the voltage divider will then be *R*1+*R*2 or 19,000 ohms. With no loads connected across the voltage divider, the bleeder current through it would assume a steady value which is determined by the resistance of the circuit and the voltage existing across it. From Ohm's law this value is found to be

$$I=E/R=\frac{250}{19{,}000}=13.2 \text{ ma.}$$

Under no-load conditions, then, a fixed value of slightly more than 13 ma is drawn from the power supply. Note that this value differs from the value of the current drawn under the load conditions shown in the illustration.

d. With load circuits *A* and *B* connected across the voltage divider, the current drawn from the power supply increases to a maximum of 70 ma. Less than half of this total current flows through the voltage divider, the greater part being shunted around the divider through circuit *A* and *B*. The remainder, representing the bleeder current, flows through resistor *R*2. The current through circuit *B* enters the divider at terminal 2 and adds to the bleeder current flowing through *R*1. This current then combines with the current from circuit *A* at the top of *R*1 and the 70 ma flows back through the positive leg of the power supply. The voltage division is accomplished as follows.

e. Since 40 ma is required by circuit *A* and 20 ma by circuit *B*, the available 70 ma divides at the ground point. The 60 ma required by the load circuits flows through ground to both circuits, and the bleeder current of 10 ma flows up through *R*2. The 20 ma drawn by circuit *B* flows through this circuit and back to terminal 2 on the voltage divider. At this point it adds to the 10-ma bleeder current and 30 ma flows through *R*1 to the top of the voltage divider. From Ohm's law, the voltage drop across *R*1 is

$$E=IR=0.030\times3{,}000=90 \text{ volts.}$$

A total of 250 volts is available between terminal 1 on the voltage divider and ground. Subtracting the 90-volt drop across *R*1 from this value leaves 160 volts available at terminal 2. The full value of the power-supply voltage from terminal 1 to ground is applied to circuit *A*.

f. The voltage divider in figure 42 has a maximum value of 30 ma, flowing through *R*1. Since d-c electrical power equals the current through a device times the voltage existing across it, the power dissipation in *R*1 is

$$P\text{-}EI=90\times0.030=2.7 \text{ watts.}$$

To avoid excessive heating, the calculated wattage of any resistor used in a voltage divider should be doubled. A 5-watt resistor can be used in this case. Where individual resistors are used in the voltage divider, the power dissipation for each resistor can be computed in this manner. However, the rating of the sections carrying only bleeder current must be computed under no-load conditions, when the bleeder current is at its maximum value.

g. Another type of voltage divider is shown in figure 43. For simplification, this divider arrangement also is shown supplying two circuits, *A* and *B*. The currents drawn by the two-load circuits flow through *R*1 and *R*2, and the values

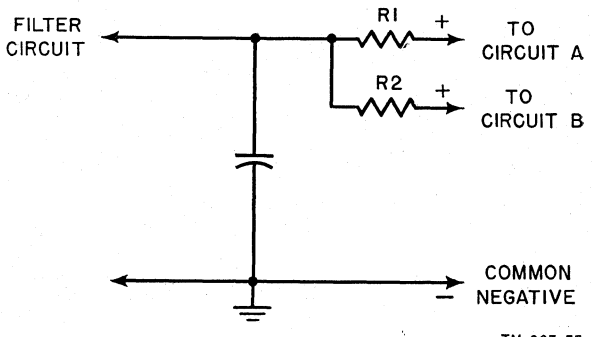


Figure 43. Inappropriate type of voltage-divider circuit. Rise in voltage across filter capacitor occurs when load is removed.

of these two resistors are so chosen that the currents flowing through them will drop the supply voltage to the values required by circuits *A* and *B*.

h. The two resistors are not connected *across* the output of the filter system in this circuit, and, therefore, do not present a constant load to the power supply. The result is that the voltage regulation is not as good as in the previous circuit. In addition, the charges on the filter capacitors cannot bleed off if the load and the power supply are turned off simultaneously. Another disadvantage is that a sudden rise in voltage occurs across the filter capacitor if the load is removed suddenly. This surge can be great enough to break down the capacitor. This voltage-divider circuit will not often be encountered because its disadvantages limit its use in most applications.

65. Typical Voltage Divider
(fig. 44)

a. This typical voltage-divider circuit provides positive voltages of different values to three different load circuits, *A*, *B*, and *C*, and furnishes negative bias potentials to circuits *A'* and *B'*. The negative voltages are obtained by establishing the ground at a point having a higher potential than *B* minus. The voltages between this point and *B* minus then are negative with relation to ground, which is taken as the zero-reference point for the load circuits.

b. Since terminal 4 (fig. 44) is grounded when current flows through the circuit, negative voltages *with relation to ground* are developed across resistor *R4*. Desired values of negative voltage can be tapped off at points *A'* and *B'* on resistor *R4*. Because the value of the negative potential increases toward *B* minus, the negative voltage at *B'* is higher than that at *A'*, a total value of 20 volts negative being available across *R4*. The negative voltages of the load circuit usually are bias voltages using a negligible amount of current. This current drain is so small that it is disregarded and the negative voltages are said to draw no current.

c. Except in the development of negative bias voltages, this voltage-divider circuit functions in a manner similar to that of the simple circuit shown in figure 42. Although 350 volts is delivered to the voltage divider from the filter system, 330 volts is the maximum positive voltage available to the load circuits. The remaining 20 volts is converted to a negative voltage supply.

d. With loads *A*, *B*, and *C* connected, the 100 ma drawn from the filter system flows through *R4* to terminal 4, causing a drop of 20 volts across *R4*. The current then divides, 85 ma flowing through the ground lead which is common to the three load circuits, *A*, *B*, and *C*, and the 15 ma bleeder current flows through *R3*. The load current in the ground lead divides into the values required by each load, 60 ma being drawn by *A*, 20 ma by *B*, and 5 ma by *C*.

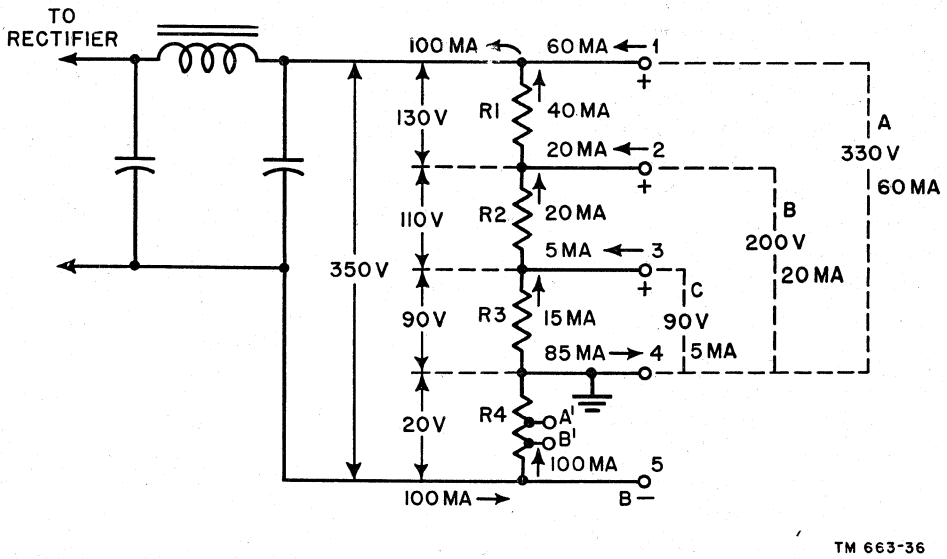


Figure 44. Voltage and current distribution along a typical voltage divider supplying positive and negative voltages to three different load circuits.

e. The 5 ma from load *C* joins the bleeder current at junction 3 on the divider and the sum of the two currents or 20 ma flows through *R*2 to junction 2. At junction 2 this current unites with the 20 ma from load *B* and the combined 40 ma continues through *R*1. At the top of *R*1, the 60 ma from load *A* joins this 40 ma, which adds up to the original 100 ma delivered by the power-supply system. The values of the four resistors are such that, with 330 volts applied between terminals 1 and 4, 130 volts is dropped across *R*1 and 110 volts across *R*2. This establishes the required load values of 200 volts at terminal 2 and 90 volts at terminal 3.

f. The values of the four sections of the voltage divider can be calculated by use of Ohm's law. The power dissipation and the required wattage rating of the divider or its several individual sections can be determined from the formula for power, $P=I^2R$, or $P=EI$.

66. Arc-Over in the Voltage Divider

a. Power supplies designed to deliver several thousands of volts present a problem in the arrangement of the resistors used as voltage dividers. Because of the high potentials between adjoining terminals, a single resistor with tapped sections generally cannot be used, since the possibility of arc-over between taps is great. In these circuits, each section of the voltage divider consists of a series of individual resistors (fig. 45) so arranged physically that the paths between points of widely differing potentials are as long as possible. This must be borne in mind when replacements are made in this type of circuit. Although it might be possible to obtain the proper wattage and ohmic value with a single resistor, the leakage path between the sections becomes so short that the hazard of arc-over becomes a definite reality.

b. Since the power dissipated in a resistor is manifested as heat, another special problem occurs in power supplies delivering high current to the load. The current through the voltage-divider sections can be so high that resistors rated for high power dissipation must be used. The resistors must be separated from each other and so arranged that excessive heat is not concentrated at any point. Good ventilation must be provided to disperse the radiated heat. If it is confined, damage will occur to adjacent parts in the equipment, and possibly to the power resistors themselves.

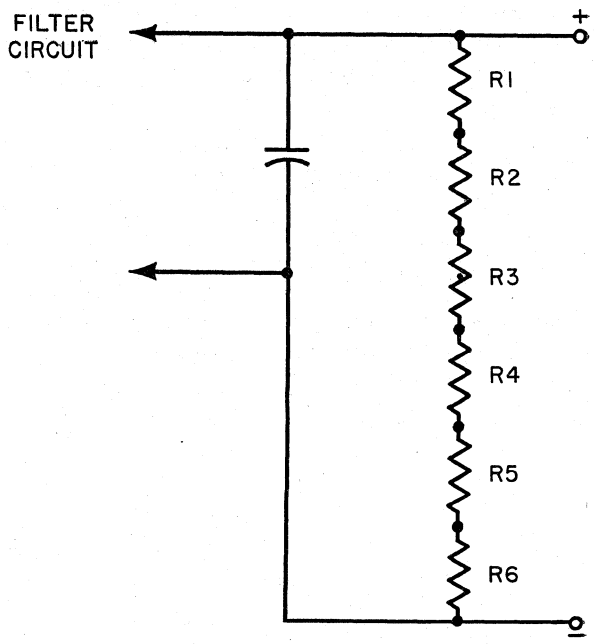


Figure 45. A series of individual resistors used in a voltage divider to eliminate arc-over.

67. Summary

a. A voltage divider usually is a tapped resistor or a series of individual resistors so arranged in the output of the power supply that voltages of various values can be obtained.

b. In addition to functioning as a voltage divider, this device when connected across the output of the power supply acts as a bleeder resistor and places a constant load on the power supply.

c. Under no-load conditions the bleeder current through a voltage divider is greater than under load conditions.

d. To provide a reasonable safety factor, the wattage rating of a voltage divider should be twice the value computed from the formula $P=EI$.

e. When a point on the voltage divider other than *B* minus is used as ground, negative voltages (with relation to ground) are obtained between the ground point and *B* minus.

f. In power supplies delivering very high voltages, the voltage divider must be so arranged as to provide a long path between points of widely differing potentials to prevent arc-over. This arrangement calls for the use of a series of individual resistors.

g. Individual resistors spaced to afford maximum ventilation are used in voltage dividers having a large current-drain and high power dissipation.

68. Review Questions

a. What is a voltage divider?

b. How is it usually connected in the power-supply circuit?

c. What additional function does it perform?

d. Why is bleeder action necessary?

e. How can the value of a voltage divider, or sections thereof, be determined?

f. How does the actual wattage rating of a voltage-divider resistor compare with the computed value?

g. How are negative voltages developed in the voltage divider?

h. What are the requirements for the arrangement of voltage dividers in power supplies delivering high voltages?

i. How should voltage-divider resistors be arranged where the current drain is high?

CHAPTER 6
VOLTAGE REGULATORS

69. General

a. A voltage regulator is an electronic device connected in the output of a power supply to maintain the output voltage at its constant rated value. It reacts automatically within its rated limits to any variations in the output voltage. Should this voltage rise or fall, the voltage regulator automatically compensates for the change and maintains the output voltage at the required value. Despite large changes in the load current drawn from a power supply, or changes in the applied input voltage, the voltage regulator maintains a constant output voltage.

b. Voltage regulators are constructed in several forms and can be connected in a number of circuit arrangements, but their basic operation is similar. The regulating action is, in effect, that of a variable resistor which responds to any changes in the current flowing through it. A basic voltage regulator circuit is shown in figure 46. The variable resistor R, connected in series with the load, acts as the voltage regulator which maintains a constant rated output voltage. The voltmeter connected across the circuit shows any variations in voltage.

c. All of the current drawn by the load passes through R, and the voltage drop across it depends on its resistance. The voltage across the load is the required value, the voltage drop across resistor R being predetermined to establish this condition. If an increase in input voltage causes the rectifier output voltage to rise, the voltage across the load rises if no regulation is present. However, if R in the circuit (fig. 46) is increased by varying the control, a larger voltage drop results. This increase in the resistance of R and in the voltage drop across it is proportional to the rise in input voltage. Consequently, the output voltage appearing across the load retains its original rated value.

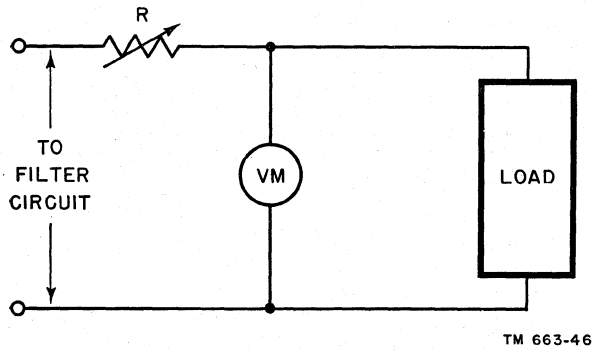


Figure 46. Basic voltage regulator.

d. Voltage regulators are designed to function over specific ranges. Electron tubes and other devices used for this purpose bear definite ratings of current and voltage and these ratings must not be exceeded. Devices used to accomplish automatic regulation of the power-supply output voltage are the Amperite voltage regulator, the glow-tube regulator, and the vacuum-tube regulator. A complicated amplifier system containing a number of these units often is used to produce the desired regulation.

70. Amperite Voltage Regulator

a. This device consists of an iron-wire resistance element, hermetically sealed in an electron-tube envelope which contains hydrogen or helium gas. The regulator plugs into a standard radio tube socket and is called an automatic-ballast or regulating tube. Hydrogen and helium are used because of their high heat conductivity and the fact that their rapid cooling extends the regulating characteristic. The iron wire has a high positive temperature coefficient of resistance which causes large variations in resistance for relatively small changes in current through it. A positive temperature coefficient indicates that the resistance of the iron wire varies directly with changes in temperature. This makes the Amperite regu-

lating device extremely sensitive to small variations in current.

b. A circuit using an Amperite regulator tube is shown in figure 47. With the load drawing normal current from the power supply, a constant voltage drop appears across the regulator tube caused by the load current that flows through it. An increase in the input voltage tends to increase the current through the regulator. The increasing current through the iron-wire resistance element increases its temperature, and so increases its resistance. The increasing resistance causes a voltage drop across the regulator tube which is proportional to the increase of the applied input voltage; this maintains the original value of voltage across the load. With a decrease in input voltage, the current through the regulator tube tends to

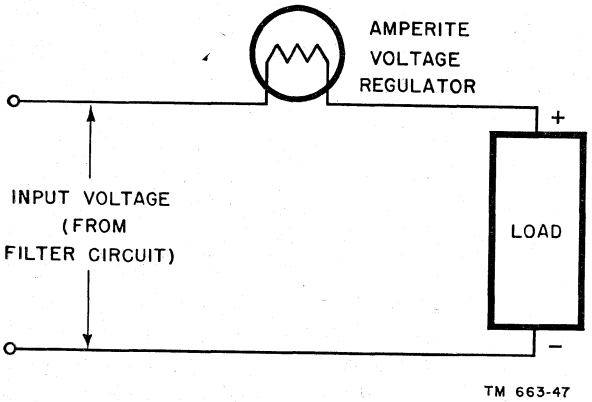


Figure 47. Amperite voltage-regulator tube connected in series with the load.

decrease. This causes the temperature of the iron wire to decrease, lowering its resistance. The lowered resistance causes a smaller voltage drop across the Amperite tube which is proportional to the fall in the input voltage, and the voltage across the load is maintained at its rated value. The rise and fall of the temperature in the iron wire caused by the changing current through it is very rapid, so that, for most practical purposes, the regulating action is in step with the variations. This is true because of the rapid cooling characteristic of the gas in the tube. The Amperite tube is known as a constant-current regulator, since varying its resistance tends to keep the current flowing through it at a constant value. This action, in turn, maintains the output voltage constant also.

c. This voltage regulator does not regulate variations in voltage caused by load changes. If the load increases, more current is drawn from the power supply and the available voltage drops in value. The increasing current increases the resistance of the regulator tube and the voltage drop across it increases. The reduced voltage across the load is made even lower by the additional drop in the voltage regulator.

d. The Amperite voltage regulator often is connected in series with several elements through which it is desired to maintain a constant current. The tube filaments in the common a-c/d-c broadcast receiver are an example of this.

71. Glow-Tube Regulator

a. One of the most commonly used voltage regulators is the glow-tube, or gaseous-discharge regulator. This is a two-element, cold-cathode tube which is filled with one of the rare gases such as neon or argon. The VR–75, the VR–105, and the VR–150 are examples of these tubes. They are designed to provide regulation at specific values of voltage. The letters VR indicate that the tube is a voltage regulator, and the numbers give the rated constant voltage which occurs across the terminals of each tube for the rated current drain. This voltage is held constant over a fairly wide range of current change through the tube. Various circuit arrangements for glow-discharge regulator tubes are shown in A, B, and C, figure 48.

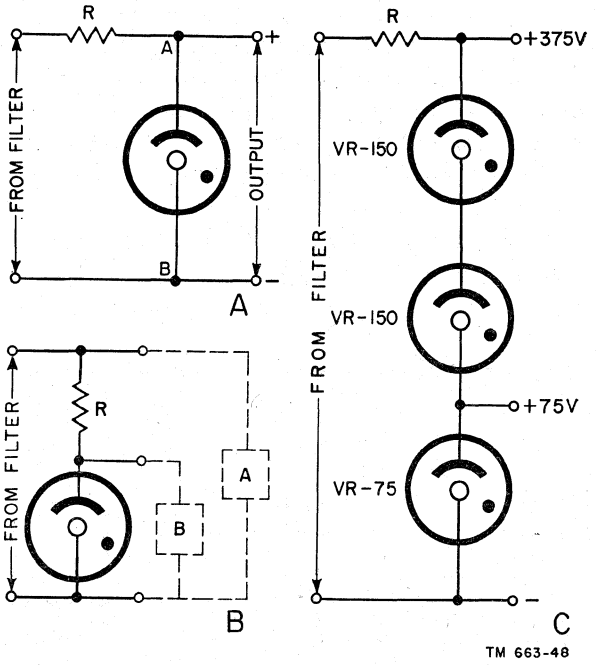


Figure 48. Three-circuit arrangements for glow-tube regulators.

b. Because the tube is filled with gas, ionization occurs when the rated positive voltage is applied to the plate. The voltage regulation obtained is a function of the degree of ionization occurring within the tube. The degree of ionization varies with the amount of current through it. When a large current flows through the tube, the gas is highly ionized and the internal impedance of the tube is low; conversely, when a small current flows, the gas is ionized to a much lesser degree and the impedance of the tube is high. The product of the current through the tube and the internal impedance, which represents the voltage drop across it, remains practically constant over the operating range.

c. An important requirement in the operation of these glow-discharge regulators is that a starting voltage somewhat higher than the value of the voltage at which the tube is rated must be present across the terminals before the tube will function. This tube also has a minimum current rating and ionization will not occur until it has been exceeded. The minimum current requirement is a consideration in the selection of the particular type of regulator to be used. Each regulator tube also bears a maximum current rating which must not be exceeded for a long period of time; if it is, the tube will be damaged.

d. In the basic circuit of A, figure 48, a glow-discharge regulator is shown connected across the output of a filter system. The series resistor, R, is required to limit the current flow through the tube so that its maximum rated value is not exceeded. This tube is rated at 75 volts, and about 100 volts must be available across points *A* and *B* before the tube will *fire*. When this condition is satisfied, the voltage output will be maintained at 75 volts over a considerable range of current drain by the load. For continuous operation, variations of 5 to 40 ma are common.

e. Another circuit arrangement, in which the glow-discharge tube functions simultaneously as voltage divider and voltage regulator, is shown in B, figure 48. In this circuit, the regulator tube and its series-limiting resistor are shunted directly across the power-supply output, which is tapped to supply two load circuits. Load *A* is the main load on the power supply but receives no regulation since it is not connected directly across the tube. The voltage applied to this load is the full value of the power-supply voltage. Load *B*, on the other hand, is connected directly across the regulator tube and has a regulated supply voltage which is equal to the constant voltage maintained by the regulator tube. In order to obtain regulation of the voltage applied to load *A*, another regulator tube of the required rating must be connected where resistor *R* is shown in the illustration. The limiting resistor then is connected in series with the output from the filter. Since it serves also to limit the current used by the added tube, its value must be altered accordingly.

f. Although the voltage rating of these regulator tubes is limited for an individual tube, two or more tubes can be used in various series circuit arrangements to accommodate a number of different voltage requirements. In this manner, 225 volts can be regulated by three VR–75 tubes in series across the output of the supply. One VR–105 tube can be used with a VR–150 tube to provide regulation at 255 volts, or three VR–150 tubes can be arranged in series to regulate a power-supply output of 450 volts. An example of these series combinations is shown in C, figure 48. This system provides two regulated output voltages of 375 and 75 volts. A tap at the junction of the two VR–150 tubes would provide a regulated output of 225 volts. However, if the additional tap is to be used, the current drain for the new load must not exceed the rated value of the top VR–150 tube.

g. An additional feature of these regulator tubes is their ability to remove ripple, or the small pulsations remaining in the filtered output voltage. A ripple represents small variations in the voltage and a regulator tube functions to keep this voltage constant. In this respect, a regulator tube acts as an additional filtering element to reduce the hum in the output.

72. Simple Electron-Tube Regulator

a. An electron tube can be considered as a variable resistor. When the tube is conducting, its resistance is the voltage existing between the plate and cathode of the tube divided by the current through it. This is known as the d-c plate resistance or *Rp* of the tube. Since the current or voltage, or both, can be varied, it follows that different values of resistance can be obtained. In an amplifier tube, for a given plate voltage, the value of *Rp* depends on the tube current, which in turn depends on the grid bias. Varying the grid bias, therefore, controls the amount of cur-

rent flowing through the tube and causes the d-c plate resistance to vary accordingly.

b. Since any amplifier tube can be used as a variable resistance, resistor *R* in figure 46 can be replaced by a triode amplifier tube. A regulator circuit using a triode tube is shown in figure 49. The d-c plate resistance of the tube *V*1 in the circuit is established initially by the bias on the tube. Assume that the voltage across the load is at the

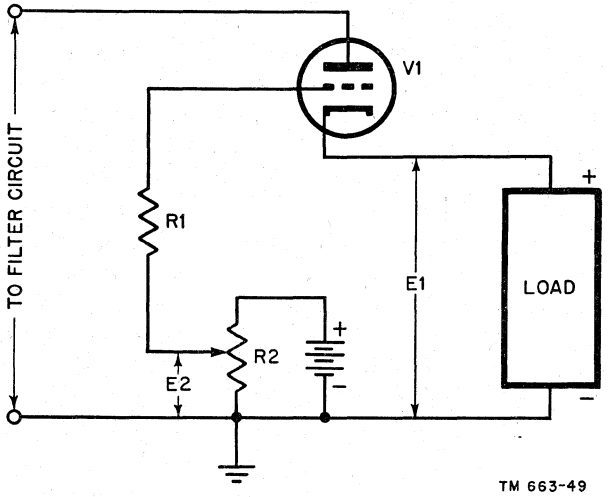


Figure 49. A simple vacuum-tube regulator using a triode tube.

desired value. Under this condition, the cathode is positive relative to ground by some value of voltage designated as *E*1. If *R*1 in the grid circuit were returned directly to ground, the grid would be negative with relation to the cathode by the amount of the voltage, *E*1. In order to reduce this bias to the proper operating value of the tube, the grid is made positive relative to ground by a voltage, *E*2, which is less than *E*1. The grid bias then equals *E*1 minus *E*2. Potentiometer *R*2 is adjusted until the bias is sufficient to allow *V*1 to pass the exact value of load current. With this applied bias, the resistance of *V*1 is established at the proper value to reduce the rectifier output to the required load voltage. The function of *R*1 is to limit the flow of grid current.

c. If the rectifier output voltage increases, the voltage at the cathode of the tube increases. Since the value of *E*2 is fixed by the setting of *R*2, the increase in *E*1 raises the bias on the tube; this increases the d-c plate resistance and the d-c voltage drop across the tube becomes greater. In a properly designed circuit, the increased voltage drop across the tube is equal approximately to the increase in voltage at the input to the regulator tube. Consequently, the load voltage remains essentially constant at the rated value.

d. In figure 49, voltage *E*2 applied to the grid of the tube is obtained from a battery. This is not a very practical method, since the battery current drain through *R*2 is uninterrupted even when the power supply is turned off. The battery can be eliminated by substituting a glow tube in place of it to supply a fixed voltage for the grid of the tube. In this circuit arrangement (fig. 50), the grid voltage is established and held constant by a VR tube. The purpose of *R*1 is to limit the flow of current through the VR tube.

e. The output voltage of the simple electron-tube regulators shown in figures 49 and 50 cannot be absolutely constant. As the rectifier output voltage increases, the voltage at the cathode of *V*1 must rise slightly if the regulator is to function. However, if the characteristics of tube *V*1 are chosen carefully, the rise in the value of the load voltage is negligible for most practical purposes.

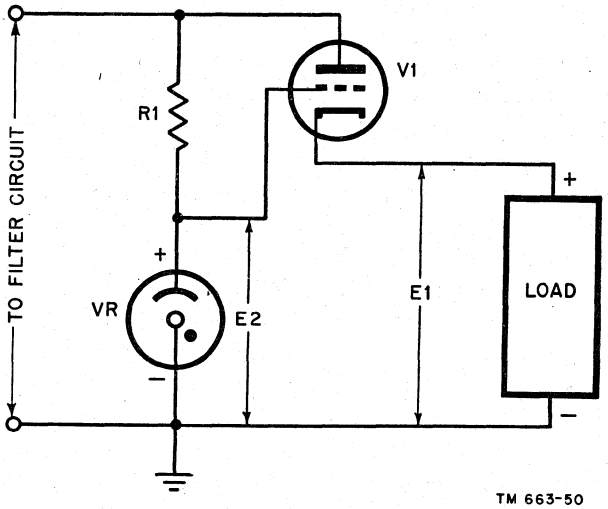


Figure 50. Vacuum-tube regulator obtaining source of grid bias from glow-discharge tube VR.

f. These simple electron-tube regulators are superior to the ballast and glow-tube types previously discussed. The amplifying property of *V*1 in figures 50 and 51 permits regulation of small voltage variations, whether these variations are caused by increases and decreases in input voltage or by changes in the load. For example, if the

load resistance in figure 50 decreases, the load current increases and lowers output voltage $E1$ by the increased voltage drop in $V1$. The cathode of $V1$ therefore becomes less positive and the bias on $V1$ is decreased, since this bias is equal to $E1$ minus $E2$. The decrease in bias lowers the d-c plate resistance of $V1$, decreasing the d-c voltage drop across the tube and allowing the load voltage to rise to the normal value. The net result is that while the total resistance across the power source (consisting of $V1$ in series with the load) is less, the division of voltage is changed so that the required rated voltage exists across the load.

73. Improved Type of Electron-Tube Regulator

a. The regulator circuit shown in figure 51 represents an improvement over the simple electron-tube types described in the preceding paragraph. In this circuit, very stable voltage regulation is obtained because of the high amplification of the pentode tube, $V2$, which increases the sensitivity of regulation for small voltage variations. Regulated output voltages that are independent of variations in input voltage or of changes in the load are obtained with this circuit arrangement.

b. The regulated output voltage appears across the bleeder resistors $R1$, $R2$, and $R3$, which are connected in series across the output of the power supply and in parallel with the load. These resistors constitute the resistance of one part of the total voltage divider. The remaining element in the voltage divider is the plate-to-cathode resistance of $V1$ through which all of the load current must flow. All of the other components in the circuit are used to control the resistance of $V1$ and so to maintain a constant load voltage.

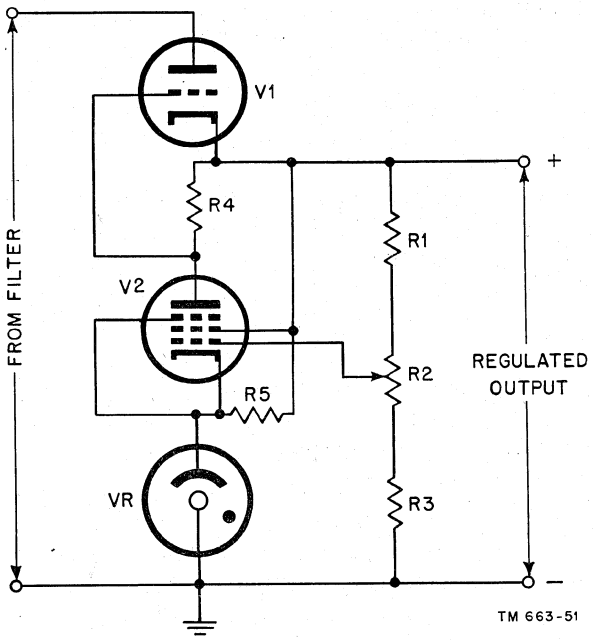


Figure 51. Circuit of a commonly used voltage regulator system using a triode, a pentode, and a glow-discharge tube.

c. The voltage appearing at the cathode of $V1$ is applied to the plate of the pentode tube $V2$ through cathode resistor $R4$. The potential of the cathode of $V2$ is maintained at a constant positive value by the VR tube. The amount of current through $R4$ and the voltage drop across it are determined by the bias on the control grid of $V2$. The grid voltage for $V2$ is obtained from the bleeder circuit. The exact value is determined by the setting of potentiometer $R2$. $R2$ is set to the point where the bias applied to the grid of $V2$ permits a specific predetermined value of current to be drawn by $V2$. $R4$ is connected between the grid and the cathode of $V1$ and the current flowing through $R4$ develops a voltage drop across it which biases $V1$ to the value of this voltage drop. Consequently, the setting of potentiometer $R2$ determines the amount of current drawn by $V2$ and establishes the internal resistance of $V1$ for the normal rated output voltage. In operation, this adjustment is used to set the value of load voltage which the regulator is to maintain.

d. If the load voltage tends to rise, either from an increase in the input voltage from the filter or because of a decrease in load current, the bias voltage on the grid of $V2$ becomes less, since a higher positive potential now exists across potentiometer $R2$. The cathode voltage of $V2$ remains practically constant because of the regulating action of the VR tube. $V2$ now conducts more current, since its bias is reduced. The increased current flows through $R4$, causing a greater voltage drop across this resistor. This increased voltage drop, which represents the bias applied to $V1$, increases the plate resistance since less current flows through $V1$. Consequently, an increased portion of the available voltage appears across the higher resistance of $V1$, and the value of the load voltage remains practically constant. The same action occurs in a reverse direction if the load voltage falls.

e. The anode of the glow tube, VR, is connected to the regulated output line through resistor $R5$.

This manner of connection is necessary in order to cause ionization of the gas in the tube when the power supply is first turned on. Resistor $R5$ establishes the proper operating voltage for the VR tube and also limits the current through the tube.

f. Since all of the load current must pass through tube $V1$, it must be capable of passing a large current. In some applications, a single tube is not able to pass the required current without damage to the tube. In such cases, two or more identical tubes are connected in parallel. Because of its increased sensitivity, this regulator is very effective in removing ripple in the power-supply output.

74. Voltage Stabilizer

a. Although the function of a voltage stabilizer is to remove fluctuations in the rectifier output voltage and maintain a steady value of output voltage, the action differs from that of the voltage regulators just discussed. The voltage stabilizer does not control the average value of output voltage, but, rather, acts to remove or suppress any a-c component or ripple that might be superimposed on the d-c voltage. A simple voltage stabilizer circuit is shown in figure 52.

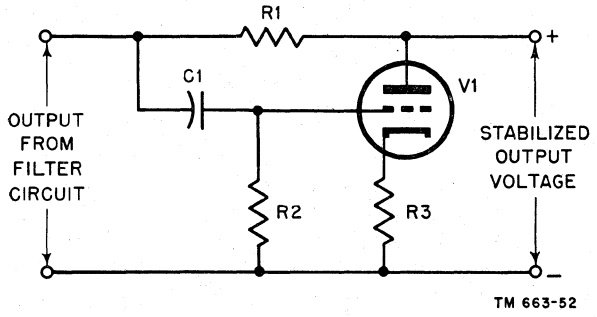


Figure 52. Basic voltage stabilizer circuit.

b. The total output current from the filter flows through resistor $R1$. Tube $V1$ is shunted across the output and draws a steady value of current depending on the value of resistor $R3$ in the cathode circuit. The voltage drop across this resistor represents the bias voltage of the tube and establishes its operating conditions. Any a-c component appearing across the circuit takes the path of least impedance—that is, through capacitor $C1$—and the d-c component is blocked. Slow changes in the average d-c output voltage do not affect this circuit because such changes are blocked by capacitor $C1$ and the tube is not activated. However, ripple voltages and transients are passed to the grid of $V1$ and the circuit functions.

c. If the instantaneous polarity of the ripple voltage is positive, it adds to the rectifier output voltage and tends to increase its value. The positive alternation reduces the bias on the grid of $V1$ and the tube draws a larger current. This current, which is drawn from the line through $R1$, increases the voltage drop across this resistor and cancels the rise in voltage caused by the ripple component. In this manner, the output voltage remains relatively constant. A similar action, but in the reverse direction, occurs when the polarity of the transient voltage is negative. The negative pulsation applied to the grid of $V1$ through $C1$ further increases the bias, reducing the current drawn through $V1$. The voltage drop across $R1$ is reduced proportionately and the output voltage retains its rated value.

75. Saturable Transformer-Core Regulation

a. When the current through a choke or transformer is increased, the strength of the magnetic field increases until a point is reached where no more lines of force can be carried by the core. At this point, the core is saturated and the magnetic field assumes a steady strength. Further increases in the amount of current through the coil have very little effect on the magnetic field or the induced output voltage. This effect results in a reduced value of coil impedance in the saturated condition. This magnetic core saturation can be utilized to regulate voltage.

b. One method of voltage regulation using saturated-core transformers is shown in figure 53. The power transformer is $T1$. $T2$ and $T3$ are the saturable-core voltage regulating transformers. Across the primaries of $T2$ and $T3$ is a variable capacitor, $C1$, forming a tuned circuit. This tuned circuit is in series with the primary of $T1$, and the series circuit is across the a-c input. Consequently, only part of the line voltage appears across the primary of the power transformer, the rest being dropped across the tuned circuit. The primaries of $T2$ and $T3$ are so connected that the a-c voltages across them are 180° out of phase with each other. Consequently, the a-c voltages coupled to the secondaries of $T2$ and $T3$ are also 180° out of phase with each other. With these secondaries connected in a series-aiding arrange-

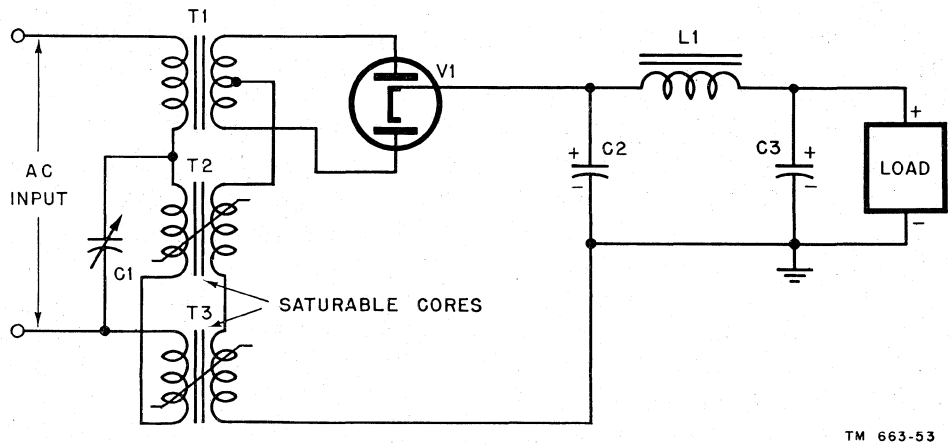


Figure 53. Use of saturable-core transformers to maintain regulated output voltage.

ment, the a-c voltage across the combination is zero. This prevents the saturable-core transformers from introducing an a-c ripple into the power-supply output. The secondary of the power transformer, $T1$, is center-tapped for full-wave rectifier action and is connected in series with the secondaries of $T1$ and $T2$.

c. This circuit operates to prevent any lowering of the d-c voltage output resulting from an increase in the load current drawn from the power supply. Because the secondaries of $T2$ and $T3$ are in series with the load, an increased load current increases the current through the secondaries. This increase in current saturates the cores of the transformers, lowering the inductive reactance of the primaries. Since inductive reactance is directly proportional to inductance, the inductance of the tuned circuit is lowered, and its resonant frequency is raised. This rise in the resonant frequency effectively lowers the impedance of the tuned circuit. Consequently, less of the input voltage is dropped across the tuned circuit, and there is a greater voltage drop across the primary of the power transformer, $T1$. This results in a higher d-c output from the power supply, compensating for the drop caused by the increased load current. By varying the capacitance of the tuned circuit, the input to the power transformer can be changed, changing the level of d-c output. This control of the d-c output level is supplied by making $C1$ a variable capacitor.

76. Regulation by Autotransformer

a. An autotransformer can be used in the input of a power supply to provide a manual control for stepping up or stepping down the applied voltage to a predetermined value. Variac and Powerstat are the trade names of two of these devices. They are connected in the a-c line on the primary side of the power transformer. A movable arm attached to a control knob can be rotated to provide a continuously variable voltage ranging from 0 to the maximum rated value of the control. A variation of this control is a tapped autotransformer which provides a similar action in steps. However, the tapped autotransformer does not afford the close control available with the continuously variable control and, therefore, is not so widely used.

b. If the power-supply primary voltage falls off in value, the autotransformer can be adjusted to step up the voltage to the required value. Conversely, should the applied voltage increase, the control can be adjusted to provide a step-down action, restoring the voltage to its original value. These manually controlled regulators often are used in conjunction with the electronic regulators previously described in this chapter.

77. Summary

a. A voltage regulator is a device connected in the power-supply circuit to maintain a constant output voltage.

b. In operation, the voltage regulator can be compared with a variable resistor which automatically adjusts its value in accordance with variations in the current or voltage.

c. The three most widely used types of electronic voltage regulators are the Amperite, the glow tube, and the electron tube.

907056°—51——5

d. The Amperite tube has an iron-wire resistance element hermetically sealed in a tube envelope which contains hydrogen or helium gas.

e. The glow-tube regulator is a cold-cathode tube filled with a rare gas such as neon, argon, etc.

f. Electron tubes (amplifiers) also are used as voltage regulators.

g. Amplifying tubes commonly are used in conjunction with glow tubes to provide a high degree of regulation regardless of variations in the input voltage or the load.

h. A voltage stabilizer is used to stabilize variations in the applied input voltage. It does not control the average value of the output voltage.

i. Transformers are used as voltage regulators acting upon the principles of core saturation.

j. When a transformer core becomes saturated, its inductive reactance and, therefore, its impedance fall off. This principle is utilized in voltage regulation, since an increase in current through a saturable-core transformer is accompanied by very little change in the magnetic field or the induced voltage.

78. Review Questions

a. What is a voltage regulator? How is it usually connected in the power supply circuit?

b. Describe the operation of a simple voltage regulator.

c. What is an Amperite voltage regulator? How is it constructed?

d. Describe the function of the Amperite regulator.

e. What gases commonly are used in a glow-tube regulator?

f. How can glow tubes be made to regulate voltages greater than their rated values?

g. Describe a simple vacuum-tube regulator.

h. Describe an improved type of electron-tube regulator.

i. Upon what does the action of a transformer voltage regulator depend?

j. Describe a basic transformer-regulator circuit.

CHAPTER 7

POWER-SUPPLY CONTROL SYSTEMS

79. General

a. A number of devices are associated with power supplies to control and direct their functions and serve as protection to equipment and personnel. These controls take the form of key switches, circuit breakers, relays, panel-interlock switches, and autotransformers. Controls also can be designed to operate signal devices that flash a light or sound an alarm when voltages and currents exceed a rated value. The common electrical fuse is a control device that opens the circuit when excessive current is drawn. These controls are connected at various points in a power supply.

b. Devices which control the application of primary power are connected in the input circuit and some input control systems are elaborate. Manual controls, such as adjustable autotransformers or tapped transformers, are connected on the primary side of the input transformer. Usually, they are manipulated after initial voltages have been applied to other sections of the power supply, such as the filaments of tubes. Input systems that are controlled automatically contain a number of relays and interlock switches.

c. Some of these controls permit remote operation of equipment, allowing the equipment to be turned on or off from a distance. Remote operation is advantageous where a number of units in different locations are controlled by one operator. Signaling devices such as meters or lights indicate when the equipment is on or off. A defect in such a control system is tantamount to a temporary breakdown in the power-supply equipment, itself, since the power supply no longer can be operated remotely, and local operation usually is not possible.

d. Although some of these controls find application in low-voltage and medium-voltage power supplies, their use is confined generally to high-voltage power supplies. *Low* voltages range from a few volts to approximately 500 volts. *Medium* voltages extend from approximately 500 volts to approximately 1,200 volts. *High* voltages range from about 1,200 volts to as high as 40,000 volts. The following discussion on control systems applies mainly to the high-voltage and medium-voltage power supplies, used in transmitters and other heavy equipment.

80. Key Switches, Circuit Breakers, and Fuses

a. Key Switches. These switches are devices that lock the power-supply input circuit in the open position to prevent application of voltage to the circuit. They guard personnel and equipment against the sudden and unexpected application of voltage through oversight or carelessness. With the switch lock in the open position and the key removed, the equipment cannot be turned on. Normally, the switch appears to be an ordinary lock. When the switch is unlocked and in the closed position, the key cannot be removed from the lock.

b. Circuit Breakers.

(1) As the name implies, circuit breakers are special switches that automatically open the circuit to protect the equipment from short circuits or overloads. They are used commonly in the primary circuits of power supplies where the voltage is comparatively low and the current high. In ordinary operation, the circuit breaker acts as a switch and controls the application of voltage to the power supply. In addition to its manual function, it automatically opens the circuit when excessive current flows through it for a given length of time. Interior sketches of a circuit breaker in the *on* and in the *tripped* position are shown in A and B, figure 54.

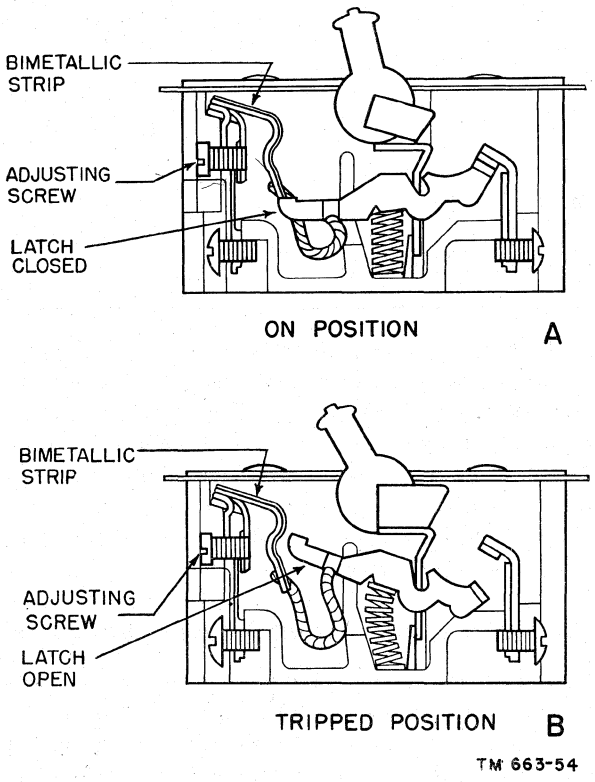


Figure 54. Low-power circuit breaker.

(2) In the usual construction, circuit-breaker action is obtained by passing the current through a heater element which activates a bimetallic strip, or by passing the current directly through the strip. The circuit breaker (fig. 54) consists of a carefully calibrated bimetallic strip, electrical contacts, and a switch arm. As current flows through the bimetallic strip, heat is generated and the strip bends. If an excessive current flows through the strip, it bends far enough to release the latch and open the contacts and therefore the circuit. When the overload is removed, the circuit breaker can be reset by operating the switch arm, or reset lever. This type of circuit breaker will carry its rated load indefinitely, a 50-percent overload for about 1 minute, a 100-percent overload for about 20 seconds, and a 200-percent overload for about 5 seconds. The 5-second interval usually is long enough to pass the high starting current required by a motor without tripping the circuit breaker. There also are magnetic circuit breakers which operate instantaneously upon the passage of more than rated current. They incorporate a magnetic tripping mechanism instead of a bimetallic strip.

(3) Circuit breakers are made in a variety of sizes ranging from the small units used in common lighting systems to the large and heavily constructed units carrying hundreds of amperes of current. Heavy-duty units usually employ manetic tripping and are incased in oil. Although fuses will protect circuits drawing upward of 600 amperes, the use of circuit breakers is growing because of their simple operation and the ease with which they can be reset. Sometimes, fuses are used in conjunction with circuit breakers to protect subordinate circuits where the use of another circuit breaker is impracticable.

c. Fuses.

(1) The most common current-limiting device in electrical circuits is the fuse. A fuse is a short length of wire or ribbon made of an alloy having a low melting point. It is designed to carry a rated amount of current indefinitely. Any current exceeding this value causes the alloy to melt and open the circuit. The ordinary house-lighting fuse opens practically instantaneously when excessive current is drawn through the circuit. Fuses designed for other uses have a delay time on overloads similar to that of circuit breakers. The delay is accomplished by making the alloy, or fuse link, of heavy construction except in one or two short portions of its length. This allows heat to be drawn away from the small high-resistance portions, delaying the melting time. Such a fuse is shown in B, figure 55. In addition to providing a delay action, which is desirable in certain applications, the fuse shown has the convenient feature of permitting replacement of burned-out elements. The cartridge fuses in A and B both have this feature. In A the fuse link is held in place by the end caps; in B the fuse link is fastened to the two external knife-terminals by screws.

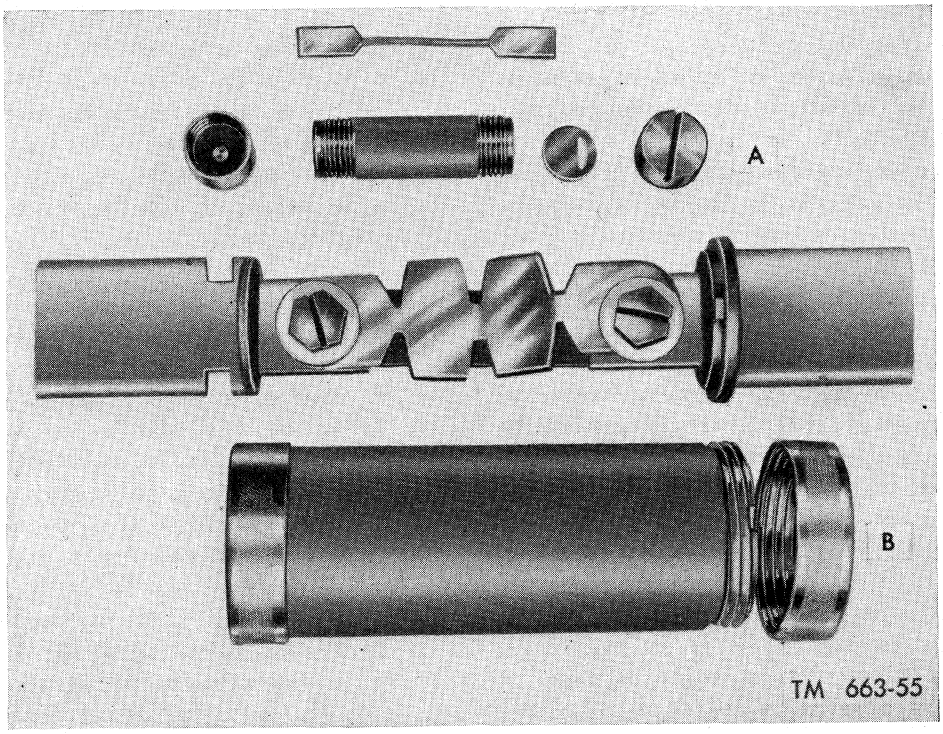


Figure 55. Cartridge fuses with removable fuse elements.

(2) The two most common fuses used in power-supply service are the round screw-in, nonrenewable fuse, which has a current-carrying capacity up to 30 amperes, and the cartridge fuse which has a range from a fraction of an ampere to 600 amperes or more. Fuse sizes above 60 amperes are constructed with knife-blade terminals, which provide better contact. Cartridge fuses up to 60 amperes have ferrule contacts. Both of these cartridge fuses can be obtained in two designs. The first provides one-time operation, after which the entire fuse unit must be replaced. The second has the renewable fuse-element (fig. 55).

81. Relay Controls

a. Relay Principles.

(1) A relay is a switch operated by an electromagnet. It is known also as a magnetic switch. Basically, it consists of a coil wound on an iron core and an armature that operates a set of contacts. The device is designed to open or close an electrical circuit when the coil is energized. A relay can be operated by a weak current, such as the output current of an electron tube, a photoelectric cell, or a thermocouple, or it can be operated from a standard power-line source.

(2) A simple relay circuit using a battery as the originating source of energy is shown in figure 56. When switch *SW* is closed, current from battery *E*1 flows through circuit *A* and energizes the relay coil. The magnetic field formed by the coil attracts the armature and pulls it against the open contacts, closing circuit *B* and

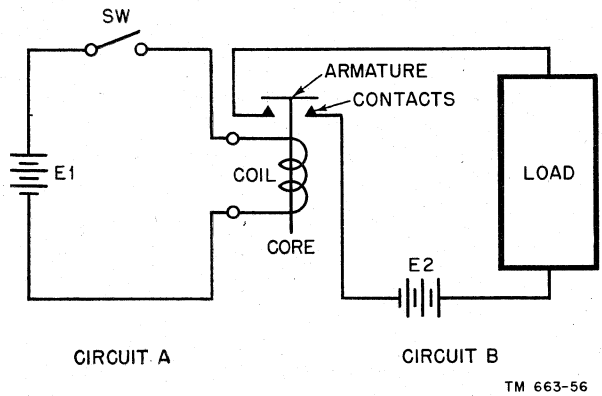


Figure 56. Simple relay switch circuit.

applying the voltage of battery $E2$ to the load. In this circuit only two contacts are shown, but relays with many contacts can be constructed for complex circuit arrangements.

(3) The operating time of a relay is the time between the closing of the coil circuit and the closing of the relay contacts. Fast action will reduce the arcing at the relay contacts and, in specially designed relays, this interval can be as short as 1 millisecond. The operating time can be decreased by reducing eddy currents in the iron core of the relay or by increasing the voltage applied to the relay coil. When slower action is desired, it can be obtained by placing a heavy copper sleeve over the core. This copper sleeve acts as a shorted turn. The induced current in the shorted turn opposes the field around the relay coil, decreases the effective strength of the field, and increases the operating time. A resistor usually is placed in series to limit the current through the coil to a safe value.

(4) Various materials are used for relay contacts. Large power relays usually have copper contacts which come together with a wiping motion to insure a good connection. Small relays have contacts coated with silver or some silver alloy. In some applications tungsten or some very hard material can be used to prevent the burning or oxidation of contacts. In general, relays that open and close with a fast, positive action have less contact trouble than those which operate slowly.

(5) Relays are constructed for operation on either a-c or d-c. A-c relays are relatively slow in operation because they are made heavy to prevent chatter and vibration caused by the alternations of the field. The chatter causes arcing and burning at the contacts. Chatter can be reduced by putting a slot in the core and placing a heavy copper washer around one half of the core. This divides the flux passing through the armature into two portions about 90° out of phase. Consequently, zero values of flux do not occur at the same time and a more uniform magnetic field cuts the armature. On sensitive a-c relays, a relay switch or locking relay is required to prevent chattering. The contacts of the relay switch are connected to the contacts of the sensitive relay. When the sensitive relay closes, one set of contacts energizes the coil of the relay switch, causing it to lock the sensitive relay into the circuit.

b. Circuit-Control Relays.

(1) The circuit-control relay is used for complex circuits requiring several switches. These relays usually are constructed with several sets of contacts for control of a number of circuits. Several circuit-control relays can be used in conjunction to perform a series of operations. The use of relays in this capacity eliminates manual operational errors by causing the various functions to take place automatically and in the proper sequence.

(2) Circuit-control relays are constructed in a wide variety of shapes and sizes. A standard type, called the switchboard relay, is shown in figure 57. A copper collar, or sleeve, is used on the relay to provide delayed action. More complex relays incorporate several sets of contacts.

c. Push-Button Operated Relays.

(1) Relay controls can be operated from a separate power source by closing a switch. Whenever possible, a momentary-contact, push-button control is used to actuate the relay coil. Some provision must be made in push-button operated relay circuits to keep the relay coil energized after the push button has been released. This is accomplished by connecting one set of relay contacts into a holding circuit connected to the energizing source of power for the relay coil. When the relay is activated, the holding contacts close along with the others, and energizing current flows through the relay coil as long as the relay circuit remains closed.

(2) Two momentary-contact push buttons, usually labeled START and STOP, are required to open and close the relay control. The START button normally is in the open position; the STOP button normally is closed. The advantage of these push buttons is that a slight pressure on

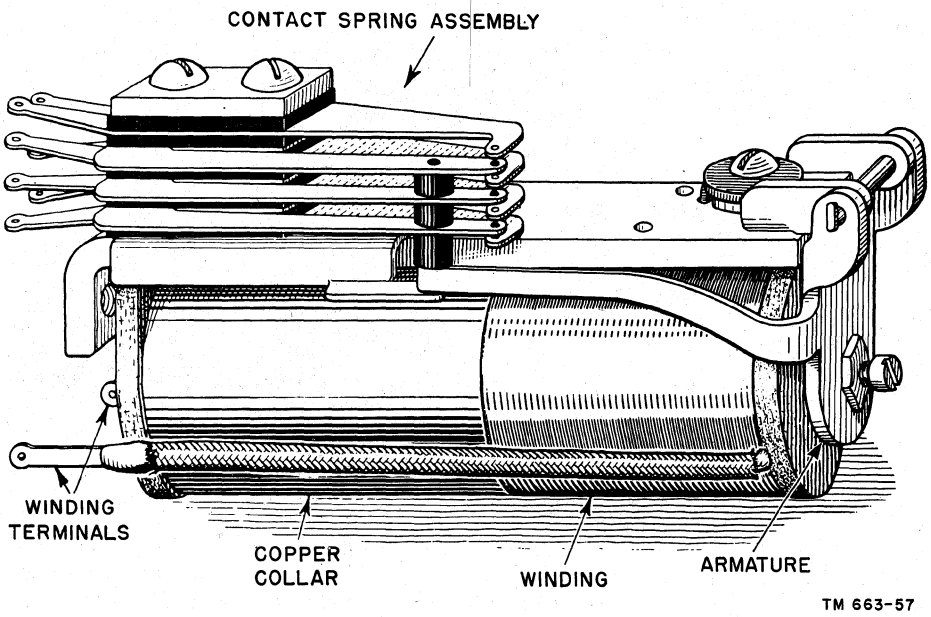


Figure 57. Basic switchboard relay.

either one is sufficient to activate or deactivate the circuit.

(3) In the push-button circuit to provide control of a high-voltage power supply (fig. 58) the relay coil is not energized until relay 2, which completes the interlock and filament circuits, is closed. With relay 2 closed, relay 1 can be closed by momentarily depressing the START button. The lowest set of contacts on relay 1 are the holding contacts. After the START button is released, the energizing current for the coil of relay 1 takes the path through the closed STOP button, the holding contacts, and through the relay coil to the other side of the input power line.

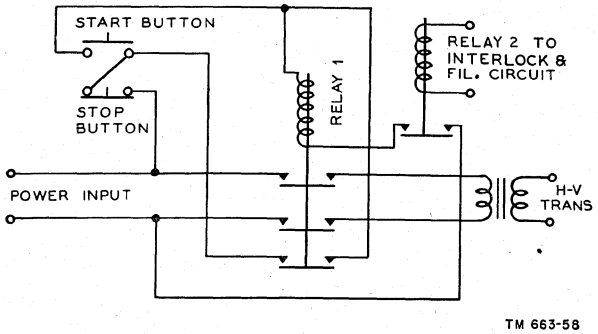


Figure 58. Relay system controlling a high-voltage power supply.

d. Time-Delay Relays.

(1) These relays provide a definite time interval between operations. The most common use of the time-delay relay is in the operation of high-voltage tubes. The relay allows a prescribed time to elapse after filament voltage is applied before plate voltage is turned on. A common form of time-delay relay uses a bimetallic element which bends as it is heated (fig. 59). The element is made by welding together strips of two metals having different expansion rates. A heater is mounted near the element. Contacts are mounted on the element itself, and, as the different expansion rates cause the element to bend, these contacts close to operate the relay. The delay time for bimetallic strips usually is from ½ to 1½ minutes. The delay time is varied by using metals with different expansion rates or by changing the distance between the fixed and movable contacts.

(2) A basic time-delay relay circuit (fig. 60) is used to delay the application of high voltage to the plates of certain tubes until their filaments have reached proper operating temperature. With the time-delay relay inactive, its armature falls

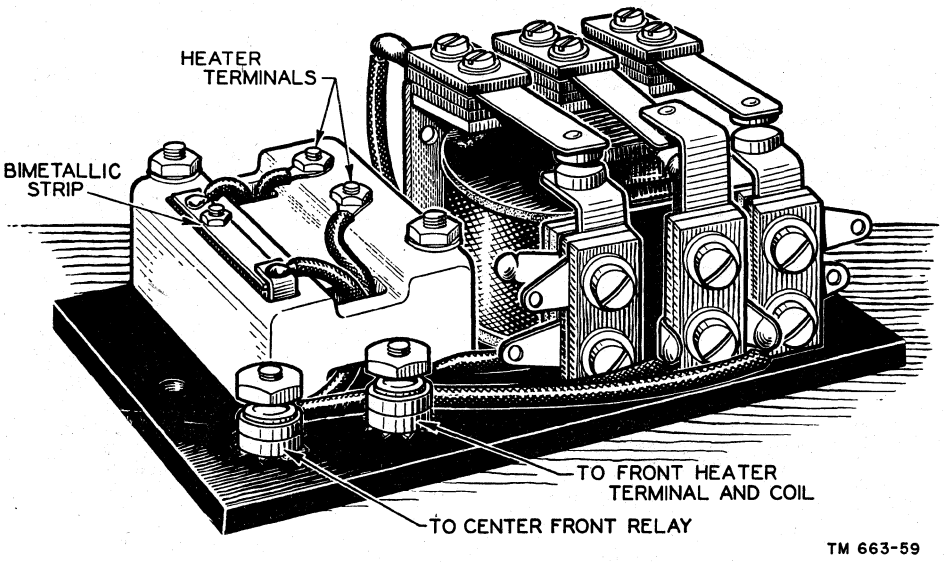


Figure 59. Time-delay relay using bimetallic element.

against the lower set of contacts and closes the relay heater circuit. This places the heater element with its series-limiting resistor directly across the a-c input line. When the a-c input switch, *SW*1, is closed, current flows through this circuit and heats the bimetallic strips.

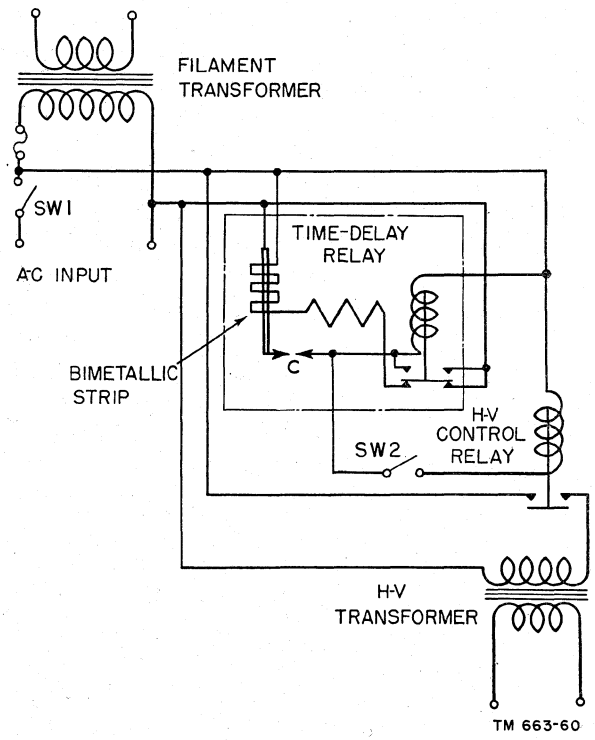


Figure 60. Use of time-delay relay in high-voltage circuit.

After the required time interval, the bimetallic strips bend sufficiently to close the contacts at point *C*. When these contacts close, the relay-coil circuit is completed across the a-c input line and current flows. With the relay coil energized, the armature is pulled away from the lower contacts and closes the upper contacts. When the high-voltage relay switch, *SW*2, is closed, the high-voltage relay coil is connected across the input line and the relay is activated, which closes the primary circuit of the high-voltage transformer. The closing of the time-delay relay opens the heater circuit and permits the heater to cool, returning the bimetallic strip to its normal position. The contacts at *C* open as the heater element cools, but the upper set of contacts on the time-delay relay serve as holding contacts to keep the coils of both relays energized, thereby applying voltage to the high-voltage transformer. Switch *SW*2 allows the high voltage to be disconnected from the circuit without affecting the operation of the filaments.

(3) Some time-delay relays use a small synchronous motor and a gear train to obtain the delay action (fig. 61). A set of movable contacts is mounted on the last gear of the train, and the circuit is closed when this set of contacts is turned until

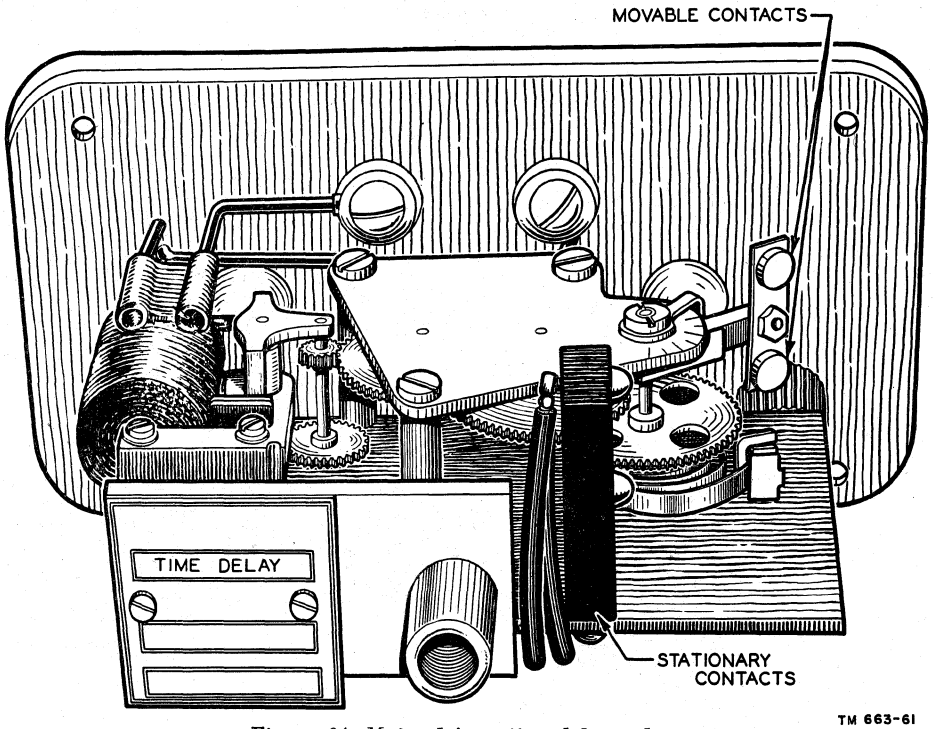


Figure 61. Motor-driven time-delay relay.

they touch the stationary contacts. Another motor-driven relay uses a spring action to close the relay contacts. The spring is released by the gear train after a given time interval.

(4) Another type is called the oil dash-pot time-delay relay. In this relay, a magnetic coil pulls a plunger through a dash pot filled with oil, the oil passing through a small hole in the plunger. The plunger is retarded the required amount as the oil is forced through the small hole. The time delay can be varied by changing the size of the hole in the plunger.

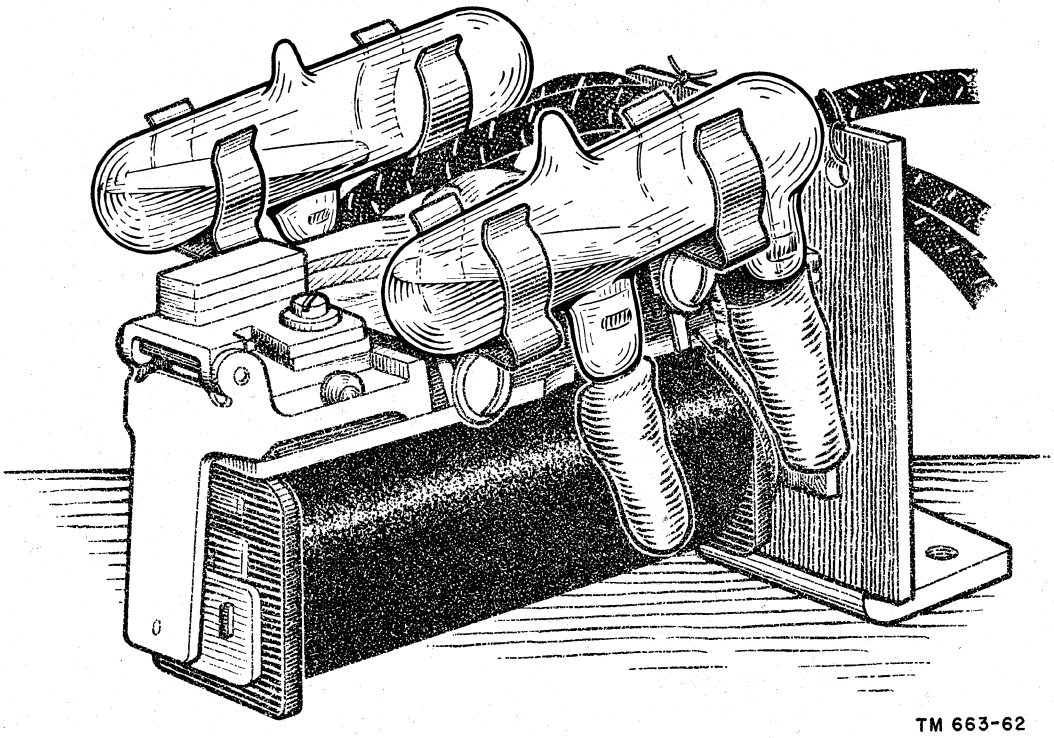
e. Power Relays or Contactors.

(1) Heavy-duty relays, called power relays or contactors, are used extensively for remote-control electromagnetic switching in power-supply circuits. In these applications a relatively small amount of control power can be used to energize the holding coil of a contactor. The relay contacts are made heavy enough to handle any required amount of power. Power relays normally are connected in the primaries of power transformers used to supply filament and plate power for electron tubes.

(2) A mercury-contact power relay (fig. 62) is used where the currents handled range from 1 to 15 amperes. The mercury and the contacts are sealed in a glass tube filled with an inert gas to prevent oxidizing of the contacts. Normally, the glass tube is tilted, and the mercury rests in one end of the tube. When the relay armature is activated, the tube is tilted the other way, and the mercury flows to the other end of the tube, either opening or closing the contacts as required.

(3) The contactor relay of the clapper type (fig. 63) has a swinging armature which is pivoted at one end. The contacts are mounted at the free end. When the relay coil is energized, the armature contacts are snapped against the stationary contacts with a clapping action. This clapper action causes the contacts to come together with a sliding motion which tends to make them self-cleaning, insuring a tight connection. Additional contacts for various control functions can be mounted on contactors of this type.

(4) Figure 64 shows a solenoid-relay contactor which operates vertically. When the coil is energized, the plunger or arma-



TM 663-62

Figure 62. Mercury-contact switch power relay.

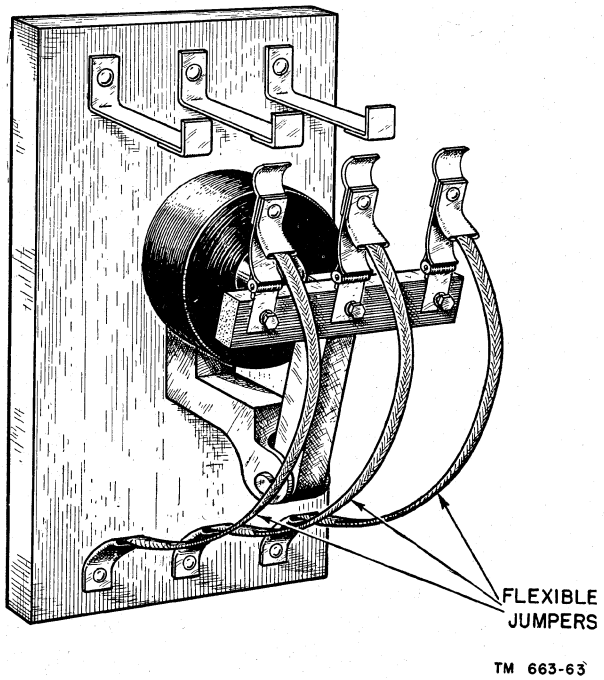


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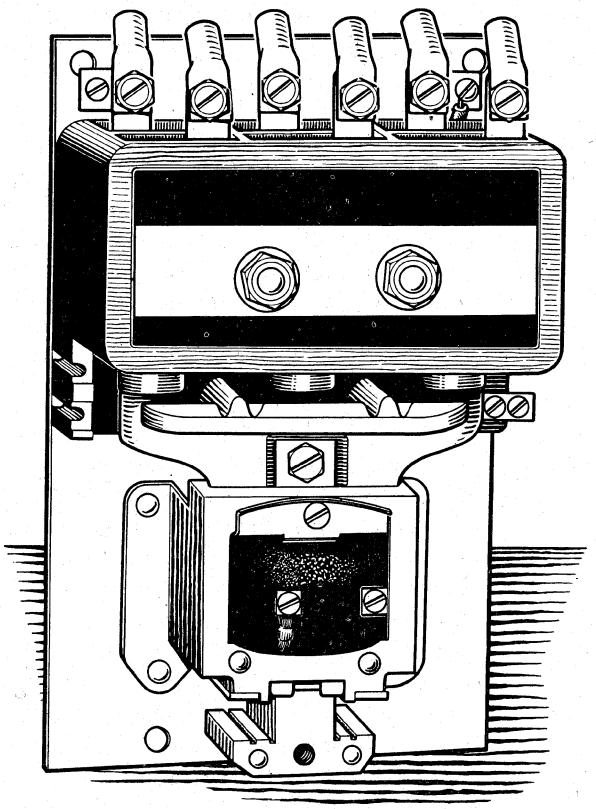
Figure 63. Clapper-type power relay using wiping contacts.



TM 663-64

Figure 64. Solenoid-relay power contractor.

ture snaps upward and closes the contacts. The contacts are mounted on springs to insure an even pressure where more than one set of contacts is used. Silver alloy contacts, which do not oxidize easily, commonly are used on these contactors to provide trouble-free operation.

f. Overload Relays.

(1) An overload relay is a protective device designed to open a circuit automatically when the current through it exceeds a certain established value. It is usually adjustable for various magnitudes of current.

(2) A current overload relay with a magnetic release is shown in figure 65. Coil $L1$ is the overload coil, connected usually in the negative lead of the circuit under protection. Coil $L2$ is the reset coil and, when momentarily energized, it resets the mechanical latch after the relay has been energized.

(3) An overload relay connected to provide protection in high-voltage circuit is shown in figure 66. The relay is connected in the B-minus, or low-potential side of the power supply to eliminate the necessity for high-voltage insulation. It is so adjusted that when the current reaches a predetermined point, the armature lifts, opening the contacts at A. This opens the circuit to the power-relay coil, de-energizing it and disconnecting the high-voltage transformer primary from the a-c input line. The weighted latch prevents the armature from falling and closing the contacts before the overload has been corrected.

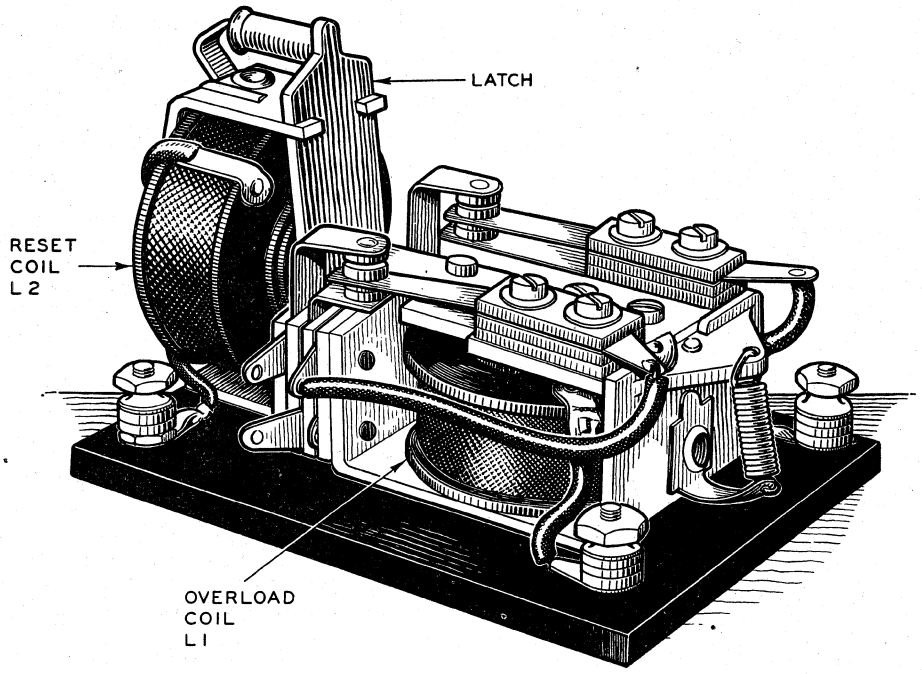


Figure 65. An overload relay with magnetic reset action.

a d-c plunger relay, in which the magnetic field of the relay coil acts upon a plunger. When the current becomes too great, the relay contacts open. A latch usually is incorporated in the relay to keep the circuit open after the relay is energized, preventing the circuit from opening and closing repeatedly while the overload exists. The relay can have a mechanical release, or reset button, to restore it to operation after the overload has been removed, or it can have an additional electromagnet for remote push-button release of the latch. These relays are

(4) Another device similar to the relay just described, and designed to protect the equipment against excessive voltages, is the voltage overload relay. Unlike the current relay, the voltage relay is connected across the line instead of in series with it. One arrangement is to connect the relay coil in series with a spark gap across the high-voltage supply, the coil being connected to the ground side. The normally closed relay contacts are connected in series with the primary input circuit. When the power-supply voltage

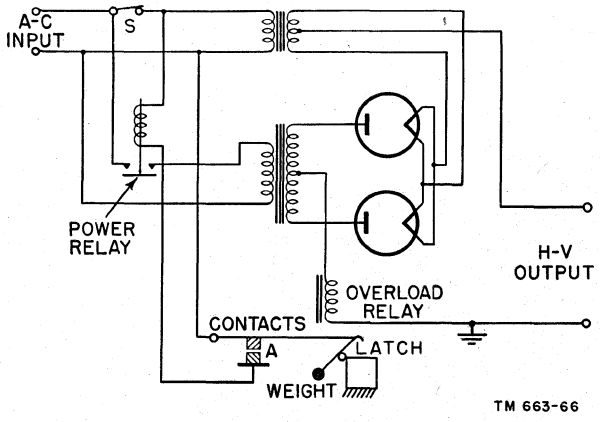


Figure 66. An overload-relay circuit protecting a high-voltage system.

exceeds a certain value, an arc is formed across the spark gap, causing current to flow through the relay coil. The energized relay coil attracts its armature, opening the contacts and disconnecting the primary of the high-voltage transformer.

82. Autotransformer Controls

a. Autotransformers are used in high-voltage or high-current circuits to control the application of power to these circuits. In high-voltage circuits, they can be used instead of, or in conjunction with, time-delay relays to prevent the application of plate voltages to electron tubes before the filaments have reached proper operating temperatures. Even after the required operating temperature is reached, the full value of high voltage usually cannot be applied suddenly to the equipment. The variable manual control provides a convenient means of applying the voltage in a series of steps over a safe period of time.

b. Examples of the use of this type of control are in the application of filament voltages and plate voltages to certain high-power transmitting tubes. Since some of these tubes require hundreds of amperes of current to operate the filaments and thousands of volts must be applied to their plates, the plate and filament voltages must be applied gradually over a period of several minutes to prevent damage to the tubes. Manual change provides a simple and convenient method of control and also can be used to compensate for any variation in the input voltages to the power supply, as explained in chapter 6.

83. Interlock Systems

a. Interlocks are devices which prevent application of high voltages to equipment until certain conditions are satisfied. When the various component units must be turned on in an orderly sequence, the interlock system prevents the turning on of any component until the preceding one has reached correct operating conditions. Usually, the system consists of a number of relay controls so arranged in the circuit that, as each one is activated, it closes the coil-energizing circuit of the next in the series. If failure occurs at any one of these controls, the following one cannot be activated. A simple example of this circuit arrangement is shown in figure 58, where the coil of relay 1 cannot be energized until relay 2 is activated, closing the circuit.

b. Interlock systems also are used to prevent high-voltage equipment from being turned on when any protective panels are removed from the equipment. This greatly reduces the hazard of injury to personnel. Spring-operated switches mounted behind the doors and panels are pressed shut when the doors and panels are closed. The interlock switches are connected in series with the holding coil of the high-voltage control relay. Opening any panel or door causes one or more switches to spring open, which breaks the circuit and de-energizes the high-voltage relay. This immediately removes high voltage from the equipment.

84. Pressure Controls

a. Many high-power transmitting tubes generate so much heat that a circulating water-cooling system is used to cool them to a safe operating temperature. The plates of the tubes are connected into the circulatory system and water is pumped continuously around them under pressure to provide the cooling function. If for any reason the pump pressure should decrease or the water should cease to flow, the high heat generated by the tubes would destroy them. Therefore, some means must be provided to shut down the equipment if failures occur in the cooling system. This can be accomplished by means of a *pressure control* that operates in accordance with the pressure existing in the circulatory system (fig. 67).

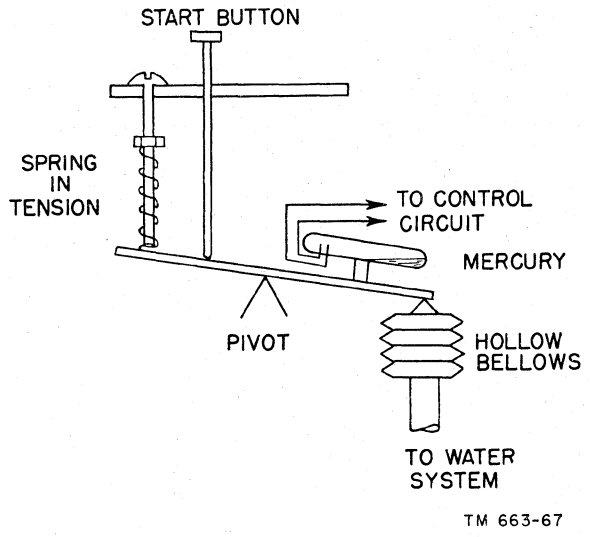


Figure 67. Low-pressure control in a water-cooling system.

b. In operation, power is applied to the pump motor and the start button is pressed to close the mercury switch. The start button is held in place manually until the water pressure is sufficient to cause the bellows to expand and hold the switch arm in the closed position. The start button then is released. If the pressure decreases because of a leak or motor failure, the bellows deflate, causing the mercury switch to open, turning off the power to the filaments and plates of the tubes. Conversely, a similar type of pressure control is used to turn off the equipment if the pressure becomes too high, as, for example, if the water circuit should clog up. An audible warning signal or other form of indication often is incorporated in the circuit to give an alarm when pressure becomes abnormal.

85. Summary

a. Control circuits in power supplies provide convenient operation and protect personnel and equipment from accident.

b. Control circuits, through a variety of devices, provide voltage and current control, automatic switching, overload protection, and indicating signals.

c. A key switch prevents the turning on of a circuit until the key is inserted and the switch unlocked. The key can be removed only when the circuit is open.

d. A circuit breaker is a switch which automatically opens a circuit when the current through it exceeds a predetermined value.

e. Fuses are current-limiting devices having a metal element with a low melting point. When the current in the circuit exceeds the rated value, the element melts and opens the circuit.

f. A relay is a magnetic switch that can be operated by a small current. Energizing a coil in the relay causes the armature to move and closes or opens various circuits.

g. Time-delay relays are designed to provide specific time-delay intervals between the time that energizing power is applied and the time the contacts close.

h. An overload relay opens the circuit when the current or voltage exceeds a predetermined value.

i. Voltage-control autotransformers are manually operated devices permitting the gradual application of voltage or current.

j. Interlock systems are protective devices which prevent the application of voltages to certain equipment until a predetermined order of conditions has been satisfied.

k. Pressure controls are control switches that are activated in accordance with pressure conditions existing in a circuit. Audible warning devices often are incorporated in the control system.

86. Review Questions

a. Name two possible functions of a power-supply control system.

b. Name some of the devices used in the control systems of power supplies.

c. Describe a circuit breaker.

d. Give the current ratings for two types of fuse.

e. What is another name for a circuit-control relay?

f. Why is fast action desirable in relay operation?

g. Describe a time-delay relay. Why is it used?

h. What is a power relay or contactor?

i. How does an overload relay function to protect the circuit?

j. How are autotransformers used?

k. Give a brief description of an interlock system.

l. What is a pressure control? Give one application.

CHAPTER 8

COMPLETE POWER-SUPPLY SYSTEMS

87. Low-Voltage Power-Supply System

a. A complete power-supply system to supply low-voltages is shown in figure 68. This circuit shows a full-wave rectifier, filter section, voltage-regulator circuit, and voltage-divider network all combined in a single power-supply unit. This circuit arrangement is typical, and if additional filtering is required, chokes or capacitors can be added after capacitor *C*2. The values of the filter components can be different from those shown, but the basic operation will be the same. The function of the power supply is summarized here in terms of the complete unit.

b. Referring to figure 68, the input voltage to the power transformer primary is 115-volt, 60-cps a-c, which is a standard value of power-line voltage. The transformer has three secondary windings, two being low-voltage windings and the third a high-voltage winding. (The term *high voltage* is used here to make a distinction between the filament voltages and the voltage applied to the plates of the rectifier tube.) In one of the low-voltage windings, the voltage is stepped down

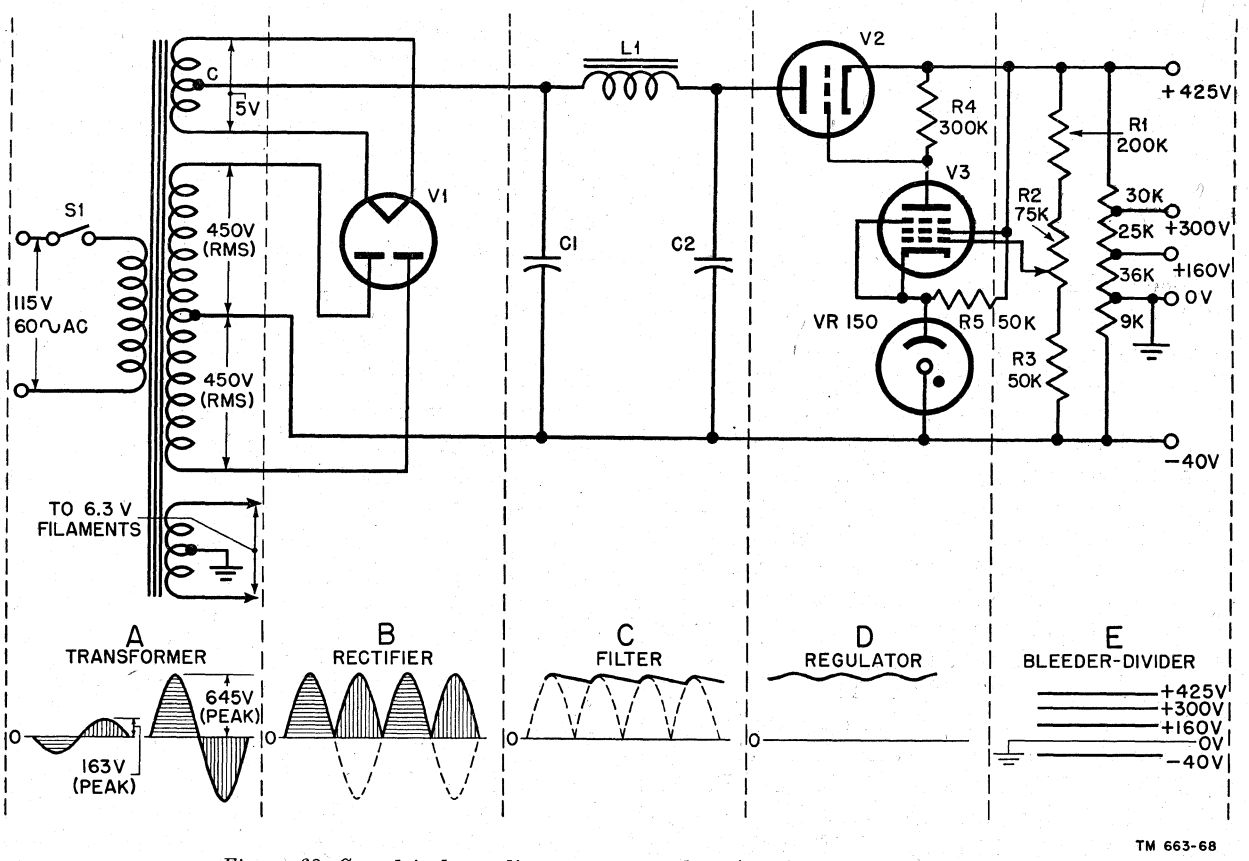


Figure 68. Complete low-voltage power supply using electron-tube regulation.

to a value of 6.3 volts and provides the power for the filaments of all 6.3-volt tubes in the power supply and its associated equipment(s). The other low-voltage winding provides a stepped-down voltage of 5 volts for operation of the filament of rectifier tube $V1$. In the high-voltage winding, the voltage is stepped up from the input value of 115 volts (rms) to a total secondary value of 1,290 volts peak to peak or 900 volts rms. This value represents a step-up of almost eight times. Waveforms showing the voltage on the primary of the transformer and the stepped-up voltage on the high-voltage secondary winding are shown in A.

c. The high-voltage secondary of the power transformer is tapped in the center to provide the common B-minus return lead for the power supply. This tap is placed at the electrical center of the winding so that equal voltages are applied to the plates of rectifier tube $V1$. From each end of the secondary winding to the center tap 450 volts (rms) is available and this voltage is applied to the plates of the rectifier tube.

d. The rectified voltage appears at the center tap of the $5V$ filament transformer in C. This winding is center-tapped so that plate current for the two sections of the full-wave rectifier will divide equally in each filament lead. The rectified pulses then will be equal in amplitude as shown in the waveform in B.

e. The operation is as follows: When switch $S1$ is closed, the 115-volt, 60-cps a-c line voltage is applied to the primary of the power transformer. This voltage is indicated by the smaller waveform in A. The larger waveform in A represents the stepped-up voltage across the full high-voltage secondary winding, which is 645 volts (peak).

f. The two plates of the rectifier tube $V1$ conduct alternately as each plate is made positive by the alternating voltage on the transformer secondary. Pulses of current flow from the filament to each plate as each plate goes positive. Since each plate is in operation for only half of an input cycle, the current through the rectifier tube always flows in the same direction as the action swings from one plate to the other. The current in the filament line, therefore, shows a continuous pulsating current flow in one direction. The waveform representing this action is shown in B. (In practice, this waveform appears only when there is no filter connected to the rectifier tube output. When the filter is used, as shown in the diagram, the actual waveform is similar to that shown in C.)

g. The rectified current pulsations are filtered and smoothed by the action of $C1$, $L1$, and $C2$ which are connected in a simple π-filter arrangement. The charge and discharge of the filter capacitors smooth the gaps between the rectified current pulses. The current flowing through the choke builds up a varying magnetic field and this field tends to retard the flow of current as it increases and to maintain the current flow when it collapses. The effect of this is to produce a more constant flow of current through the circuit. The waveform at the filter output, in C, is represented by the heavy line superimposed upon the peaks of the dotted current pulses. The capacitor input filter of the circuit allows a higher voltage output with a lower load current than that of a choke-input filter. However, a choke-input filter would provide a more constant value of output voltage with less ripple under changing load conditions.

h. The voltage-regulator circuit provides a constant value of output voltage despite variations in the input voltage or changes in load conditions. The pass tube $V2$ is in series with the output circuit. Resistor $R4$, tube $V3$, and glow tube VR–150 are connected in series across the output. The VR tube holds the cathode of $V3$ at a constant potential with respect to ground. The setting of potentiometer $R2$ determines the bias on the control grid of $V3$. The current passing through resistor $R4$ establishes the bias voltage which determines the internal resistance of $V2$. These conditions all are set to provide the rated current across the voltage divider. When the load draws a larger than rated current, the terminal voltage of the power supply tends to decrease. This places a more negative bias on the grid of $V3$, and less current flows through $V3$. The reduced current through $R4$ provides a less negative bias on the grid of $V2$, and decreases the internal resistance of this tube. Consequently, the voltage drop across the tube becomes less and the output voltage increases. In a well-designed circuit, the reduced voltage drop across tube $V2$ is just sufficient to compensate for the reduced output voltage and the voltage across the output terminals of the power supply is restored automatically to the rated value. When the terminal voltage increases, a similar action occurs in the opposite direction, and the output voltage remains constant. The output voltage

appearing across $R4$, $V3$, and the VR tube is a fairly constant d-c voltage, as shown in D.

i. The bleeder-divider resistor connected across the power-supply output performs three functions. As a bleeder, the resistor acts as a safety device to permit the filter capacitors to discharge when the equipment is turned off. As a load resistor, it acts as a stabilizer to protect the voltage regulator when no load is connected to the power supply and also helps to improve the regulation. As a voltage divider, it is tapped at various points along its length to provide intermediate values of the maximum voltage across the power-supply output. The bleeder-divider resistor can be grounded at the lower end, or it can be grounded at some point of higher potential along its length in order to provide negative voltage, or voltages, between the grounded point and B minus of the power supply. In E, three positive outputs and one negative output (−40 volts) are obtained. Their polarities are shown with relation to ground.

88. Medium-Voltage Power Supply

a. There is little difference between a low-voltage power supply and a medium-voltage power supply intended to deliver voltages up to 1,500 volts. Although the component parts of the medium-voltage power supply are of necessity heavier and more rugged to withstand the stress of the higher potentials, the circuit arrangement is similar in most respects. The a-c voltage applied to the rectifier must be sufficient to provide the required voltage delivered at the output of the power supply. The filter circuit can consist of one or more sections, depending on the amount of ripple that can be tolerated in the output. A voltage regulator and a voltage divider may or may not be used, depending on the application.

b. Usually, a medium-voltage power supply is designed to deliver a single value of d-c voltage, a separate supply being used to provide any required low voltages. However, there are exceptions to this rule, one being a medium-voltage power supply designed to supply voltage to the plate of a cathode-ray tube in an oscilloscope. The basic circuit for this power supply is shown in figure 10. A standard half-wave circuit has a series of resistors connected across the power-supply output, tapped at intervals to provide the operating potentials for the elements of the tube.

89. High-Voltage Power Supply

a. Figure 69 shows a high-voltage power-supply circuit which uses a number of controls mentioned in the previous chapter. This power supply de-

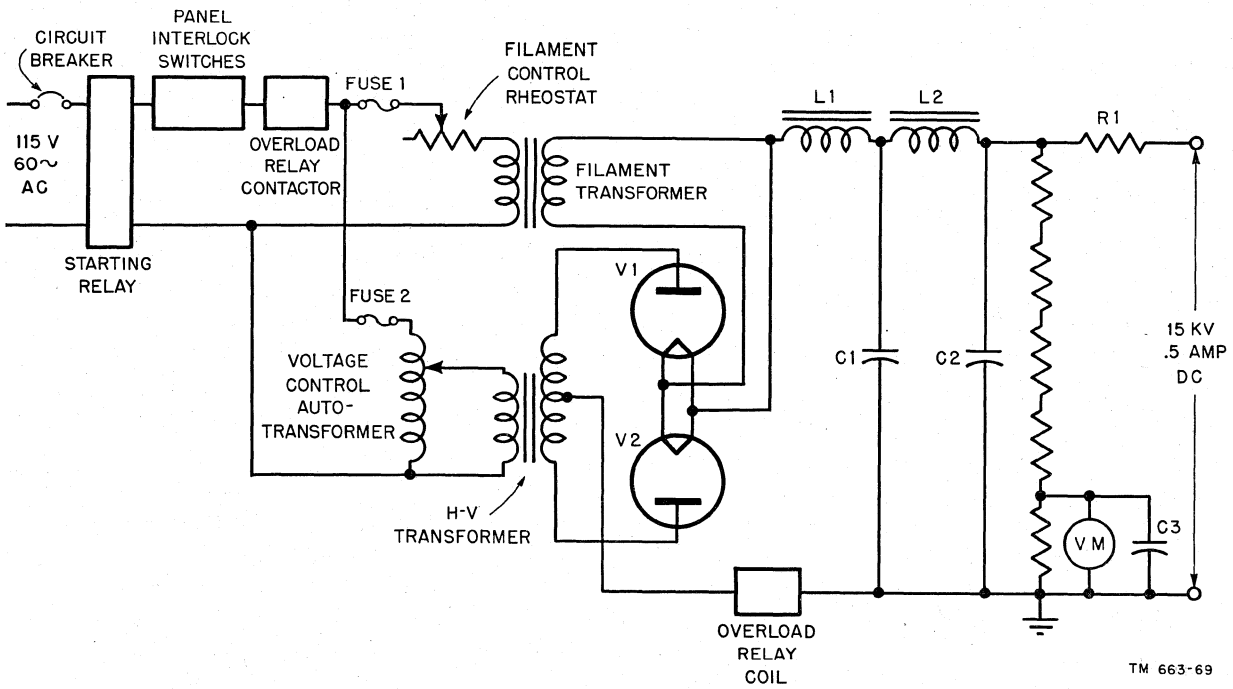


Figure 69. High-voltage power supply incorporating circuit control and protective devices.

livers 15 kilovolts and 0.5-ampere d-c to a transmitter. Two separate transformers supply filament and plate voltages for the rectifier tubes, and manual controls incorporated in the primaries permit gradual application of the filament and plate voltage to the rectifier tubes.

b. The component parts of this power supply are large and ruggedly constructed to withstand high-voltage stresses. The rectifier plate transformer is incased in oil to provide proper cooling and to prevent arc-over between its terminals in humid areas. A series of individual resistors in the bleeder network, spaced to cover a large area, provides a maximum cooling effect and a minimum arc-over hazard. Resistor $R1$ acts as a suppressor to prevent oscillations in the transmitter from feeding back to the power supply and building up undesirable signal voltages across the power-supply impedance.

c. In operation, the circuit breaker must be closed manually before the input voltage can be applied to the transformer primaries. A key switch (not shown) can be used ahead of the circuit breaker. The circuit breaker is adjusted to break the circuit automatically if an excess of current should be caused by a short circuit or if a line surge should occur. Before the application of input voltage to the power supply, both controls in the transformer primaries must be turned to the zero-voltage position.

d. When the starting relay switch button is actuated, the relay coil is energized and the contacts close. This completes the a-c input circuit to the interlock switches. When the panel interlock switches and the overload relay contactor are closed, voltage is available for the transformer primaries through the two manual controls. Fuses 1 and 2 are incorporated to provide individual protection for the transformers.

e. With input voltage available across the transformer controls, the next step is to apply voltage to the rectifier-tube filaments. This is done by adjusting the filament control rheostat to apply correct operating voltage to the filaments. Usually, the control is turned to a preset mark on the panel, or the applied filament voltage is read on a meter and the adjustment is made accordingly. After a prescribed time interval, voltage can be applied to the rectifier plates through the voltage control transformer. An output voltmeter is connected across a section of the bleeder resistor and calibrated to interpret the reading of the voltage drop across this section in terms of the total voltage output. Capacitor $C3$ protects the meter against steep voltage surges and stray r-f currents. The voltage control autotransformer is adjusted in steps until the rated output voltage is read on the output voltmeter. The input voltage must be applied slowly in order to prevent damage to the tubes and circuit components. The two L sections of the choke-input filter consisting of $L1$, $L2$, $C1$, and $C2$ provide the filtering.

f. The coil for the overload relay is connected in series with the common ground lead and the center tap on the high-voltage transformer secondary. The overload-relay contacts are in series with the a-c input line. These contacts normally are closed when the relay coil is not energized. The overload relay is adjusted to operate when a current exceeding a determined value flows through the coil. For example, any abnormal current drain caused by a short circuit in the power supply or in the equipment being supplied, or by excessive loading actuates the overload relay and opens the contacts in the input line. This instantly removes the applied input voltage from both transformers and shuts off the power supply. The overload relay must be reset before the power supply can operate again and this cannot be accomplished until the abnormal condition is cleared. This device affords the maximum protection against excessive current drains occurring in the d-c voltage supply system.

g. The interlock switches shown in figure 69 are of the panel type and prevent application of voltage to other equipment until all panels are in place, eliminating the shock hazard to personnel. The interlock system also can include a series of relay switches which must be actuated in a definite sequence before the interlock system is closed so that input voltage can be applied to the power supply. This interlock system is used when a number of equipment component units must be placed in operating condition before the application of high voltage.

h. High-voltage power supplies will be encountered that differ in detail from the one shown, but basically, their operation will be the same. More (or fewer) control devices can be incorporated in the circuit but their functions will be similar; they provide facility of operation, maximum protection, and highest efficiency.

90. Combination of Power Supplies

a. Two or more power supplies operating from the same power transformer but independently of each other can be combined in one basic unit. Combination supplies are used where two independent output voltages are needed to satisfy equipment requirements. The output voltages can be of the same polarity, or the output of one supply can be positive and the output of the other negative. The values of the output voltage can be the same for each power supply, or one can provide a low voltage while the other provides a high voltage to independent circuits. With the exception of the power transformer, separate components are required for the individual rectifying and filtering circuits. A standard transformer can be used, but it must be rated to fulfill the current requirements of the combined circuits. Usually, the transformer is designed for combined operation, having either additional rectifier filament windings, or taps on the high-voltage secondary winding to accommodate the combined circuits.

b. Figure 70 shows a simple combination of two individual power supplies. The plates of the two rectifier tubes are connected in parallel across the secondary winding, which is center-tapped to provide full-wave rectification. The rectified voltages on the cathodes of the tubes are fed to separate circuits where they are filtered and then applied to separate loads. They also are positive in polarity in respect to ground and approximately equal in value. Because of the parallel connection of the rectifier plates, the tubes function in unison to provide full-wave rectification in the output of each power supply.

c. Another example of a combination power supply is shown in figure 71. Here, a low-voltage, full-wave rectifier, VI, delivers to load 1 a voltage that is positive with relation to the ground tap *B* on the transformer secondary. The other half of the dual supply is a separate and an individual high-voltage supply delivering to load 2 a voltage which is *negative* with relation to ground.

d. The power transformer secondary is a single continuous winding tapped at several points. *B* is the grounded tap and is common to both circuits, being negative for the low-voltage supply and positive for the high-voltage supply. *A* and *C* on the secondary winding connect to the two plates of the full-wave rectifier tube, *V*1, and provide them with the out-of-phase voltage required for full-wave rectification. The tapped sections of the transformer secondary indicated as *A*, *B*, and *C* function like any conventional, center-tapped, high-voltage secondary furnishing input voltages to a full-wave rectifier. As each of the two plates in *V*1 swings alternately positive with relation

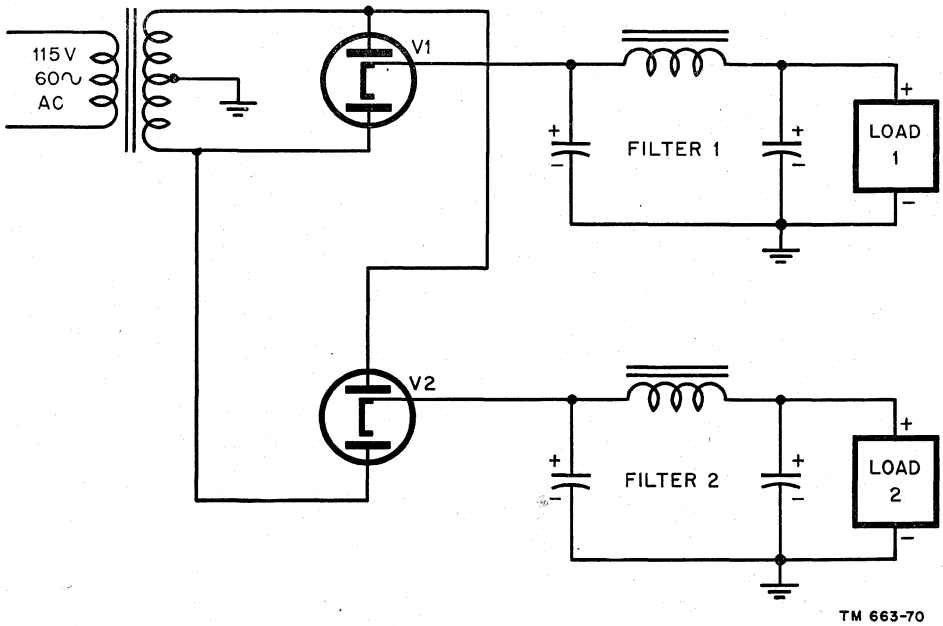


Figure 70. Combination power supply showing two independent outputs obtained from one conventional power transformer.

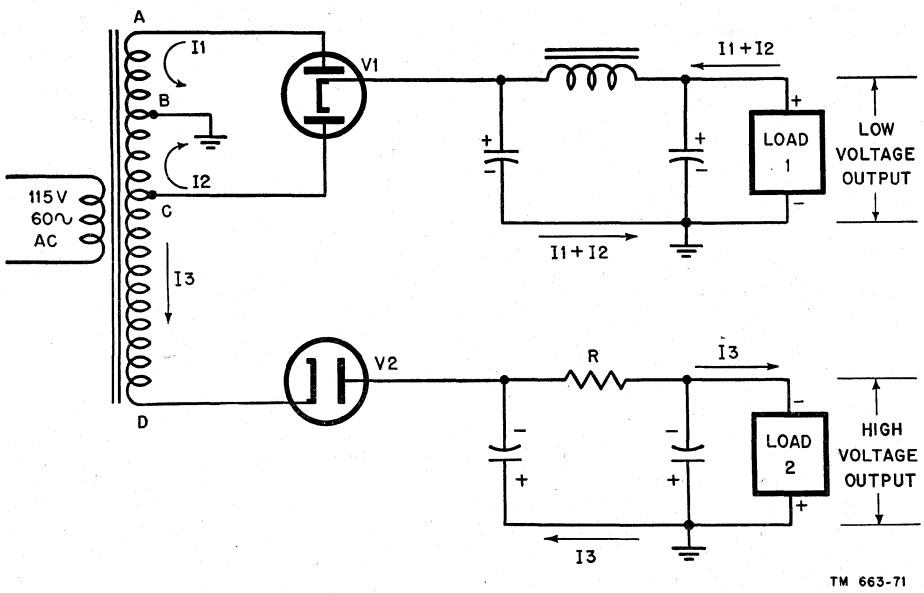


Figure 71. Two-purpose power-supply system consisting of a low-voltage full-wave rectifier and a high-voltage half-wave rectifier.

to the common cathode, electrons flow through tube $V1$ in the direction shown by the arrows, $I1$ and $I2$. The polarity of the voltage across load 1 is positive with relation to ground, as indicated.

e. Considering the other section of the secondary winding in figure 71, a voltage exists between the grounded tap, B, and the bottom end of the winding, D. The magnitude of the voltage between these two points depends on the turns ratio between the primary of the transformer and the tapped section between B and D of the secondary winding. The use of this section of the winding to supply a separate rectifier system with $V1$ has no effect on the second rectifier tube $V2$. The fact that the grounded tap at B is negative for the low-voltage supply does not determine its polarity for the high-voltage section. Ground, as a reference point, can have either polarity.

f. The section of the transformer secondary between B and D (fig. 71) supplies voltage to rectifier tube $V2$, and the voltage across these two points is alternately positive and negative in accordance with the input voltage. On one alternation D becomes positive with relation to B, and on the next alternation, D is negative with relation to the grounded tap. The cathode of $V2$ is connected to D and, when this point is positive, the tube is blocked and no current flows through it. However, on the next alternation, when D becomes negative, the cathode of tube $V2$ becomes negative with relation to its plate, and conduction occurs. Current then flows through the high-voltage circuit in the direction shown by the arrow, $I3$. The complete circuit is from D and the cathode of $V2$ through tube $V2$, resistor R, and load 2 to ground. Since the ground point and the B tap on the secondary winding are connected and have a positive polarity, current $I3$ flows into tap B and completes the circuit through the high-voltage winding, returning to D. Because of the direction of current flow through the circuit, the polarity of the voltage across load 2 is negative with relation to ground as shown.

g. In this manner, the two power supplies function independently of each other to provide outputs of opposite polarity and different magnitudes of voltage. The magnitudes of voltage depend on the turns ratio between the transformer primary and the tapped sections of the secondary. The polarity of the output voltage depends on the circuit arrangement. For example, if rectifier tube $V2$ had its *plate* connected to D on the secondary winding, the current through this circuit would be in the opposite direction and a positive polarity would exist across load 2.

91. Application of a Combination Power Supply

a. General.

(1) Numerous arrangements of combination power supplies are used in military applications. Figure 72 shows a three-pur-

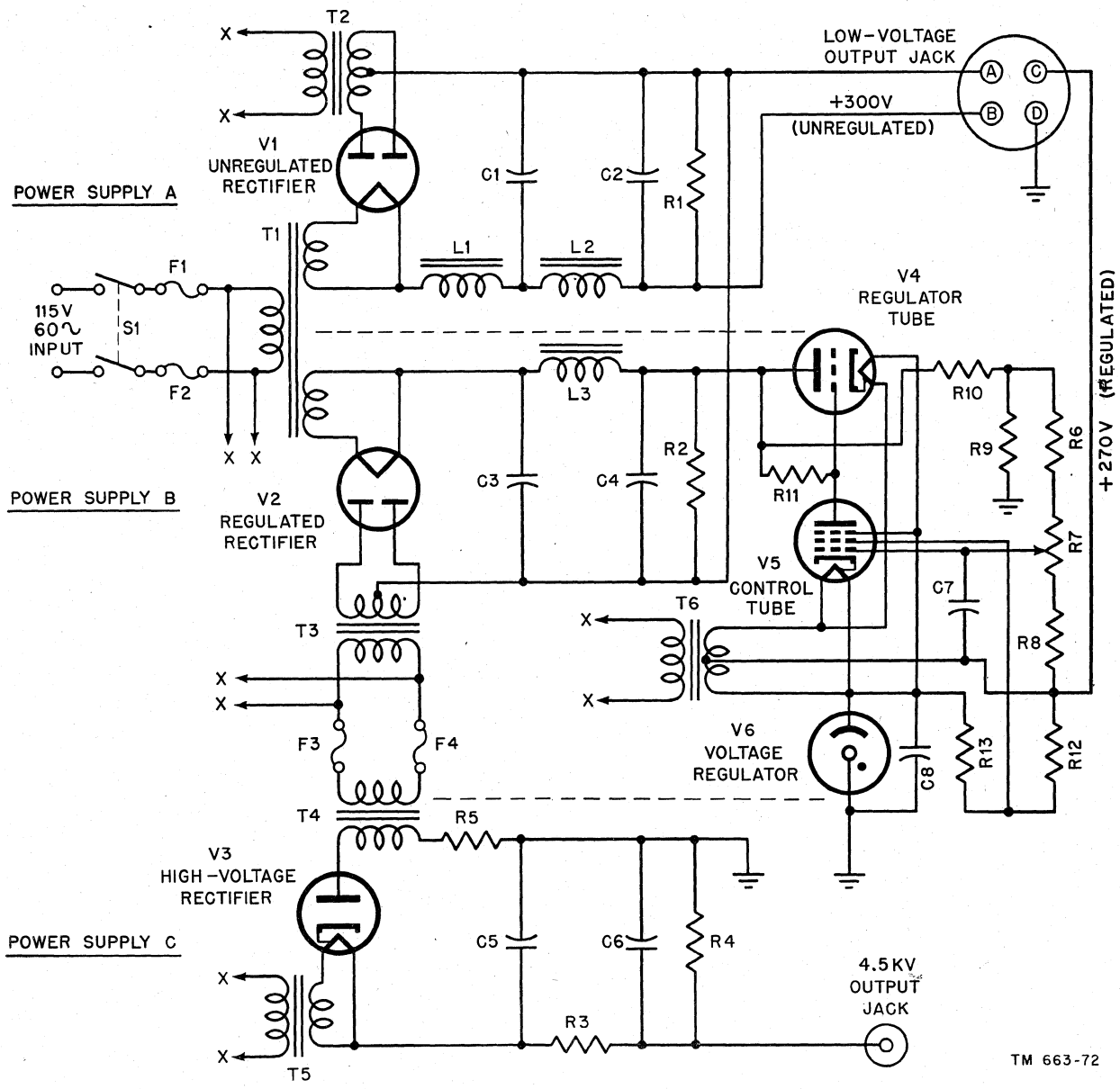


Figure 72. Three-purpose power-supply system.

pose power supply furnishing voltage to various circuits in a radar indicator unit. These outputs (all positive) are an unregulated 300 volts, a regulated 270 volts, and an unregulated 4,500 volts. The 300-volt and the 270-volt outputs are used to supply plate and screen voltages to all the stages in the indicator. The supply voltage that is used for a given stage depends on the voltage regulation requirements of that particular stage. If voltage regulation is needed, the 270-volt supply is used; otherwise, the 300-volt supply can be used. The unregulated 4,500-volt supply provides the high voltage needed for the cathode-ray tube circuit.

(2) When switch *S*1 is turned on, an input of 115-volt, 60-cps a-c is supplied to all the filament and power transformers in the power supply. Five-ampere fuses, *F*1 and *F*2, are in series with the primary of transformer *T*1 to protect the power-supply circuits. Two ½-ampere fuses,

$F3$ and $F4$, in the primary of the high-voltage supply filament transformer, $T4$, give added protection.

b. Unregulated 300-Volt Supply. The unregulated 300-volt positive output is obtained from power supply A (fig. 72) which is a conventional full-wave rectifier with two sections of choke-input filtering. Filament voltage for the duo-diode $V1$ is taken from the secondary of transformer $T1$. The line voltage to the plates of $V1$ is applied to the primary of transformer $T2$. The choke-input filter consists of $L1$, $C1$, $L2$, and $C2$. The output is a d-c voltage relatively free of a-c ripple. A bleeder resistor, $R1$, is placed across the output. The bleeder serves to protect personnel by discharging capacitors $C1$ and $C2$ when the power supply is turned off. The 300-volt unregulated output appears across pins A and B on the output jack.

c. Regulated 270-Volt Supply.

(1) The regulated 270-volt positive output is obtained from power supply B. The first section of power supply B consists of a full-wave rectifier and a π filter. $V2$ is the duo-diode used; $C3$, $L3$, and $C4$ form the π filter. Filament voltage is obtained from a secondary winding of $T1$. The 115-volt, a-c input to the plates of $V2$ is applied to the primary of transformer $T3$.

(2) The second section of power supply B is a voltage regulator consisting of tubes $V4$, $V5$, and $V6$. If the output voltage (at pin C of the output jack) tends to decrease, the grid-bias voltage of $V5$ decreases, causing it to conduct less, and increasing its plate voltage. This rise in plate voltage is coupled directly to the grid of $V4$. Consequently, $V4$ conducts more current. This increase in conduction causes a decrease in the d-c plate resistance, causing a smaller voltage drop to appear across the tube. The smaller drop across the tube causes a greater drop to appear at the output, compensating for the original decrease. The process is reversed if the output voltage attempts to increase. The cathode of $V5$ must operate at a fixed potential so that only voltage variations at its grid cause current through the tube to increase or decrease. To keep the cathode at a fixed potential, voltage-regulator tube $V6$ is used. Capacitor $C8$ bypasses to ground any fast changes in output voltage and keeps them from appearing at the cathode of $V5$. Resistor $R7$ is made variable so that the regulator circuit can be adjusted for a positive output voltage of 270 volts under normal load conditions. Resistor $R10$ compensates for changes in line voltage by coupling a part of any change in the filtered output of the rectifier to the grid of $V5$. Capacitor $C7$ makes $V5$ sensitive to rapid changes in the rectifier output by coupling the full voltage change to the grid.

d. Unregulated 4,500-Volt Supply. The high-voltage output is obtained from power supply C (fig. 72). A half-wave rectifier is used to provide the unregulated 4,500-volt positive output for the cathode-ray tube circuit. The current drain from this section is relatively small. The output of $V3$ is filtered by resistor $R3$ and capacitors $C5$ and $C6$. The bleeder resistor $R4$ draws about 1 ma of current, improving regulation as well as acting as a safety device. Resistor $R5$ protects $V3$ by limiting the initial surge of current through it. The high-voltage output appears across bleeder resistor $R4$. The output of power supply C is applied to the cathode-ray tube through a special output jack.

92. Summary

a. Several low-voltage windings often are incorporated in power transformers to provide filament voltages for the tubes used in the equipment.

b. When a filament-rectifier tube is used, the rectified voltage is taken from the rectifier filament winding. This winding usually is center-tapped so that the plate current in each half of the rectifier tube divides equally in each filament lead.

c. Filter elements $C1$, $L1$, and $C2$ in figure 68 form a simple π filter.

d. In a well-designed voltage-regulator circuit, the voltage regulator compensates for any tendency of the output voltage to vary within prescribed limits.

e. Little difference exists between a low-voltage power supply and a medium-voltage power supply; the primary difference is in the physical size of the circuit elements.

f. Power transformers used in high-voltage power supplies usually are incased in oil to provide cooling and reduce arc-over.

g. Protective devices, such as fuses, circuit breakers, and overload relays, may be used in all types of power supplies to prevent excessive current drain with attendant damage.

h. Switching relays, interlock systems, and both manual and automatic controls are used to apply voltage in the proper sequence to high-power circuits.

i. Combination power supplies providing outputs independent of each other can be incorporated in one basic component supplied by a power transformer common to the combined circuits.

j. The voltage outputs of the combined circuits can be of the same or of opposite polarity. Also, the magnitudes of the voltage can be equal or unequal depending on circuit arrangement.

k. Specially constructed power transformers usually are required in the applications of combined power supplies.

93. Review Questions

a. Why should the center tap on the power transformer secondary winding be at the electrical midpoint?

b. When a directly heated rectifier tube is used, where is the rectified voltage usually taken from?

c. Why are several low-voltage windings usually included in power transformers?

d. What is the purpose of the *VR* tube in the voltage-regulator circuit shown in figure 68?

e. To what degree does a voltage regulator compensate for variations in a power-supply circuit within rated limits?

f. Name three provisions usually incorporated in a high-voltage power-supply circuit to provide protection against excessive current drain.

g. In what position should the manual voltage controls be when applying input voltage to a high-voltage power supply?

h. Could voltage be applied to the high-voltage circuit in figure 69 if an interlock switch were open?

i. Why must voltage be applied gradually to the rectifier tubes in a high-voltage circuit?

j. Where in the circuit would the coil of an overload relay usually be placed?

k. Are combined power-supply circuits dependent on each other in operation?

l. What determines the magnitude of the voltages obtained from a dual power supply?

CHAPTER 9

R-F POWER SUPPLIES

94. General

a. The basic radio-frequency power supply uses a local oscillator operating at radio frequencies to provide the equipment with the required operating potentials. A typical application is a high-voltage, low-current supply for the anode of a cathode-ray tube. The radio frequencies generated by the oscillator are approximately 200 to 300 kc (kilocycles) but can range from 50 to 500 kc. The generated frequencies can be much lower and sometimes fall within the audio-frequency range. The alternating voltage is stepped up by means of a tuned autotransformer and then is applied to a rectifier tube which converts the alternating voltage to the required d-c voltage.

b. Some of the disadvantages of the 60-cps and other low-frequency power supplies are eliminated when r-f power supply is used. The step-up transformer used in r-f power supplies is much less bulky than the conventional low-frequency power transformer. The r-f power supply has a high ripple frequency and the rectified voltage requires only a small amount of filtering, which permits the use of very small filter elements. The filter elements consist of low-value capacitors and high-value resistors of low wattage, since the current drain from this type of power supply is not appreciable. The small filter capacitors reduce the hazard of electrical shock since they cannot store a lethal charge. In addition, the body capacitance introduced when a section of the r-f oscillator circuit is touched detunes the circuit, reducing the voltage output substantially. The magnetic field surrounding the r-f power transformer is much less than that surrounding a 60-cps transformer supplying similar voltage; consequently, unwanted hum modulation of the signal is reduced. However, the r-f power supply must be shielded to prevent the oscillator frequency or a multiple thereof from appearing as an undesired signal in the operating equipment. Because smaller circuit elements can be used, the r-f power supply is much lighter and more compact than a 60-cps supply with a similar value of output power, and provides a much greater economy of cost and space. In addition, the output voltage from the r-f power supply can be raised conveniently to extremely high values by the use of multiplier stages consisting of additional tubes and several small capacitors and resistors.

c. Three basic types of r-f power supplies are the conventional r-f power supply, the triggered r-f power supply, and the fly-back or kick-back power supply. Each of these power-supply circuits is discussed below.

95. Conventional R-f Power Supply (fig. 73)

a. $V1$ is used as a tuned-plate, tickler feedback oscillator. The frequency of oscillation is changed by the setting of the variable trimmer capacitor $C2$. Grid-leak bias for the oscillator tube is supplied by resistor $R2$, capacitors $C4$ and $C5$, and tickler coil $L3$. The 300-volt plate and screen operating voltages for the oscillator tube are furnished by a separate low-voltage supply. The r-f transformer has four windings, $L1$, $L2$, $L3$, and $L4$, which are all wound on the same core. $L1$ is the primary winding and, when tuned to the resonant frequency by capacitor $C2$, acts as the oscillator tank circuit across which the oscillator output voltage appears. Secondary winding $L2$ has many more turns than primary winding $L1$ and therefore the voltage induced in the secondary is many times greater than the voltage existing across the primary of the transformer. Winding $L3$ is the tickler feedback coil used for feedback in order to maintain oscillations. The small winding, $L4$, supplies r-f filament power to the high-voltage half-wave rectifier tube, $V2$.

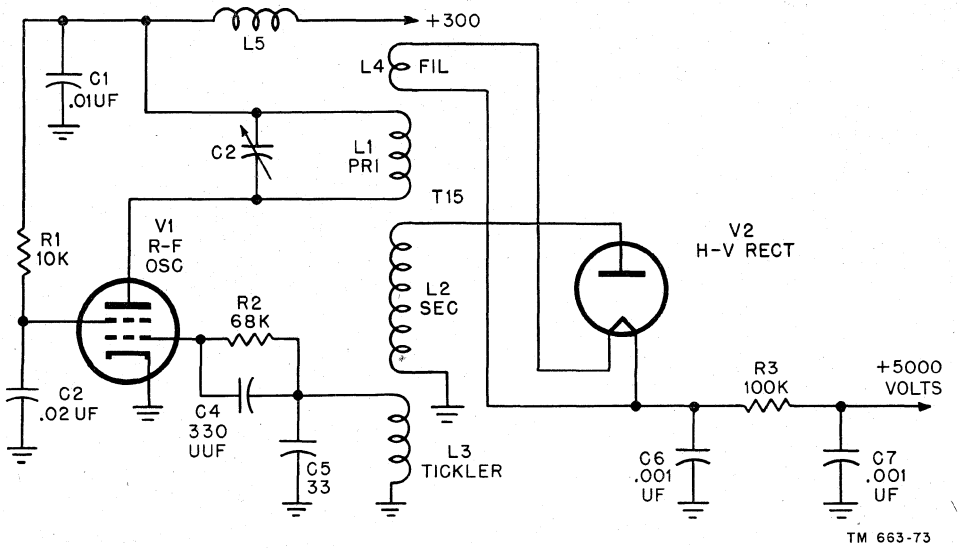


Figure 73. A typical r-f power-supply circuit providing 5,000 volts of d-c output voltage.

b. The rectifier tube is specially designed to operate with low filament power. The r-f voltage, induced in filament winding $L4$, heats the filament of this tube to the proper operating temperature. This method has a decided advantage over heating the filament with current from a 60-cps source. If current from a 60-cps source were used, it would be necessary for the high-voltage filter circuit, $R3$, $C6$, and $C7$, to filter out the 60-cps hum frequency introduced in the high-voltage line by the filament current, and large and bulky circuit elements would be required. In addition, it is safer for personnel to handle this equipment because of the small values used for $C6$ and $C7$. Also, by heating the filament with r-f, the high-frequency ripple can be removed easily. Note that the size of the filter capacitors are only 0.001 μf each. The high value of filter resistor $R3$ (100,000 ohms) can be tolerated since the current drain from such a supply is comparatively small.

c. The L-C (inductance-capacitance) combination consisting of coil $L5$ and capacitor $C1$ forms a decoupling filter to keep r-f out of the separate 300-volt power supply. Resistor $R1$ drops the screen voltage to the required value, and capacitor $C3$ bypasses any signal voltage existing on the screen grid to ground.

d. As previously mentioned, primary winding $L1$ is tuned to the oscillator resonant frequency by adjustment of capacitor $C2$. The resonant frequency of the secondary winding is determined by the shunting capacitance resulting from the rectifier tube, and the stray circuit capacitance caused by wiring and circuit components. The voltage across $L2$ is maximum when the frequency of the oscillator is made equal to the natural resonant frequency of $L2$ in parallel with the shunting capacitance. The circuit is designed so that the maximum voltage that is obtainable across $L2$ is greater than the required output voltage. The required value of output voltage is obtained by adjusting tuning capacitor $C2$.

e. The high voltage induced in secondary winding $L2$ is applied to the plate of half-wave rectifier $V2$ and current flows through the tube every time a positive alternation of oscillator voltage makes the plate of $V2$ positive with relation to its filament. The rectified d-c voltage, which is pulsating at the frequency of the oscillator, is taken from the filament of the rectifier tube and fed to the filter circuit consisting of $C6$, $R3$, and $C7$. The ripple component is filtered easily by these circuit elements because of the high frequency at which it occurs. If a higher value output current is required, an identical r-f oscillator tube can be connected in parallel with the existing oscillator tube.

96. Triggered R-f Power Supply
(fig. 74)

a. Sometimes the fundamental frequency of the r-f power-supply oscillator, or any of its harmonics, causes interference with other equipment operation, even though the power-supply circuit is well shielded. This interference can be elimi-

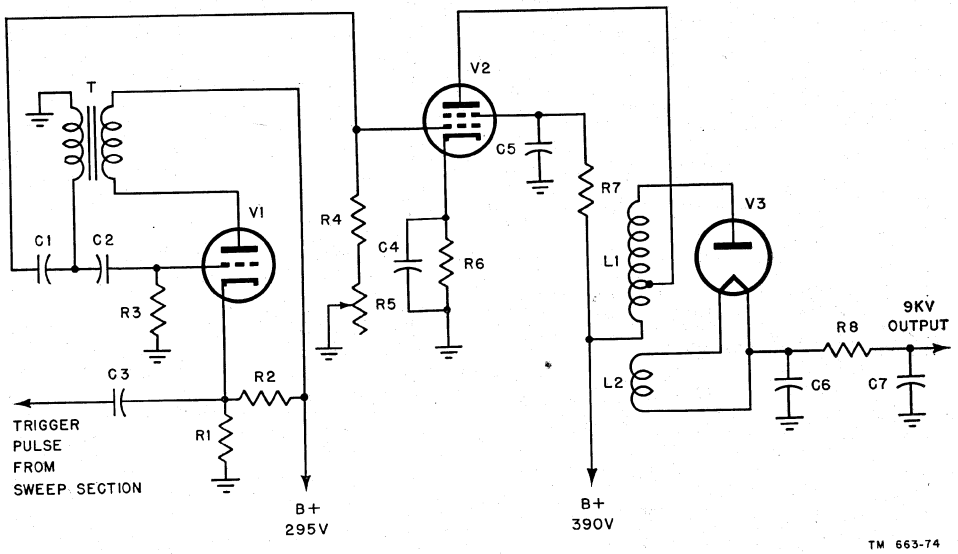


Figure 74. Triggered, or pulse-actuated, r-f power-supply circuit.

nated by permitting the r-f oscillator to function only during set intervals. In the triggered or pulsed r-f power supply the period of oscillation is governed by incoming pulses which actuate the circuit.

b. Tube $V1$ functions as a blocking oscillator. Tube $V2$ amplifies the r-f voltage, and $V3$ rectifies the high r-f voltage which is stepped up in coil $L1$. A portion of the r-f voltage in $L1$ is induced in $L2$ to provide filament power for the rectifier tube.

c. Resistors $R1$ and $R2$ form a voltage-divider network across the 295-volt B supply. The positive voltage across cathode resistor $R1$ places a high negative bias on $V1$ and does not allow the circuit to oscillate until a trigger pulse is applied to the cathode through coupling capacitor $C3$.

d. The oscillator output voltage is taken from the feedback transformer, T, and is applied to the grid of $V2$ through coupling capacitor $C1$. the r-f signal is amplified by stage $V2$. The amplified r-f signal appears across coil $L1$ and is adjusted by the setting of rheostat $R5$ which determines the bias of $V2$. Resistor $R7$ in the screen-grid circuit of $V2$ drops the applied voltage to the value required by the screen grid. Capacitor $C5$ bypasses any a-c signal that appears on the screen grid.

e. Coil $L1$ functions similarly to an autotransformer and steps up the amplified voltage from $V2$ to a much higher value. The lower tapped section of coil $L1$ represents the primary and is connected as the plate load of $V2$. The secondary, or upper tapped section, has many more turns than the primary in order to provide the desired value of step-up voltage applied to the plate of rectifier tube $V3$. On each r-f alternation, when the plate of $V3$ is positive with relation to the filament, a pulse of rectified current flows through the tube. These high-frequency pulses are filtered out by capacitors $C6$ and $C7$ and resistor $R8$ and a d-c voltage of 9 kilovolts appears across the output of the power supply.

f. The frequency at which oscillations occur when the oscillator circuit is triggered is established by the values of capacitor $C2$ and resistor $R3$ in the grid circuit of $V1$ and transformer T. This transformer is a powdered-iron core r-f transformer and is designed specially for operation in pulse-actuated circuits.

97. Fly-Back High-Voltage Power Supply (fig. 75)

a. The fly-back, or kick-back, power supply is used primarily to supply a high d-c voltage at low current to the accelerating anodes of cathode-ray tubes. In this power supply no separate high-frequency oscillator is needed. A separate low-voltage power supply is required to provide plate and screen voltages for $V1$.

b. Transformer T consists of a primary winding (between 1 and 3) which is tapped at 2 to provide autotransformer action. $L1$ is the pri-

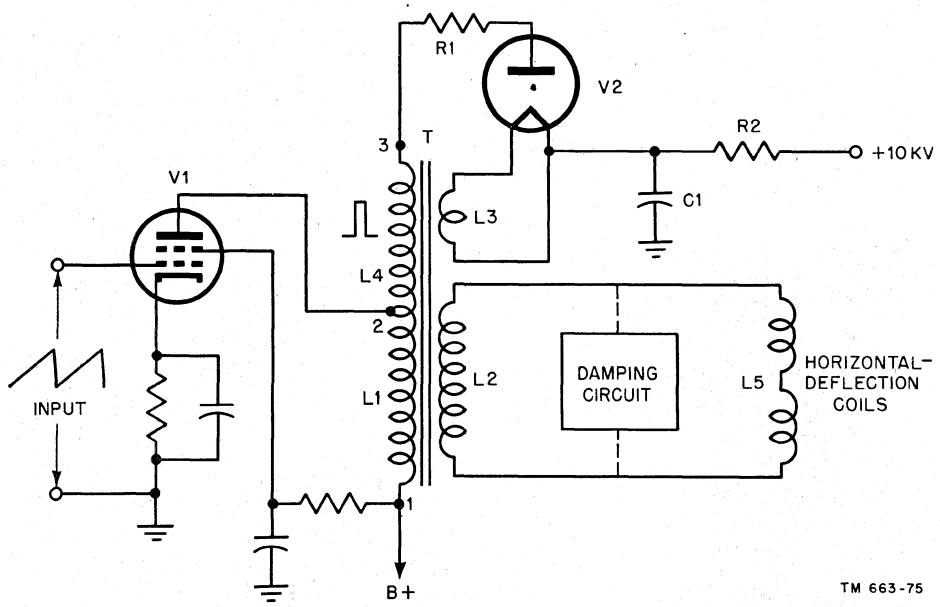


Figure 75. Schematic diagram of typical fly-back high-voltage power supply.

mary of the autotransformer and is in the plate circuit of tube $V1$. The stepped-up voltage across the entire winding, between 1 and 3, is applied to the plate of $V2$ through the current-limiting resistor $R1$. $L2$ is the secondary of the transformer and provides energy to the horizontal-deflection coils. Winding $L3$ of the transformer furnishes r-f power to heat the filament of rectifier tube $V2$.

c. Inductance $L5$ represents the horizontal-deflection coils that are associated with electromagnetic cathode-ray tubes. Through the action of $V1$ and the horizontal-deflection coils, $L5$, a voltage pulse is generated that excites transformer T. This provides a high-voltage pulse that is applied to the plate of rectifier tube $V2$. The pulse is rectified by $V2$ and is filtered by the R-C (resistance-capacitance) circuit $R2C1$ to provide a 10,000-volt output.

d. $V1$ is a beam power amplifier capable of handling large currents. Its main function is to amplify the input sawtooth and supply a large current to $L1$.

e. A sawtooth waveform is applied to the control grid of $V1$ and eventually appears across the horizontal-deflection coils of the cathode-ray tube where it is used for deflection purposes. The sawtooth waveform also causes the transformer and the deflection coils to break into oscillation. This causes a large d-c voltage to appear at the output of $V2$. The frequency of the input sawtooth determines the rate at which oscillations begin.

f. During the time the sawtooth input is increasing, the current through $L1$ increases, causing a magnetic field to be built up around it. When the sawtooth reaches its peak value, $V1$ is conducting maximum current. The plate load of $V1$ consists of transformer T and the horizontal-deflection coils. (Transformer T matches the impedance of the deflection coils to the tube.) The plate load of this tube is therefore inductive and any sudden change in current through the load will induce a high-voltage pulse. A sudden change takes place during the fall in sawtooth voltage at the input to $V1$. The horizontal-deflection coils, transformer T, and the stray capacitance in the secondary $L2$ form a resonant circuit which is shocked into violent oscillation by the sudden collapse of the current flowing in the circuit. The first half-cycle of oscillation is a large amplitude negative pulse which appears across $L2$. This induces a large amplitude positive pulse in $L1$. The positive pulse is stepped up to a higher value by the autotransformer action of $L1$ and $L4$. It then is applied to the plate of rectifier tube $V2$. After rectification and filtering by $R2$ and $C1$, a positive output of approximately 10,000 volts is obtained in the output.

g. In practical applications any oscillation beyond the first half-cycle is undesirable, since it affects the linearity of the deflecting voltage. Consequently, a damping circuit is placed in parallel with the deflection coils to damp out all oscil-

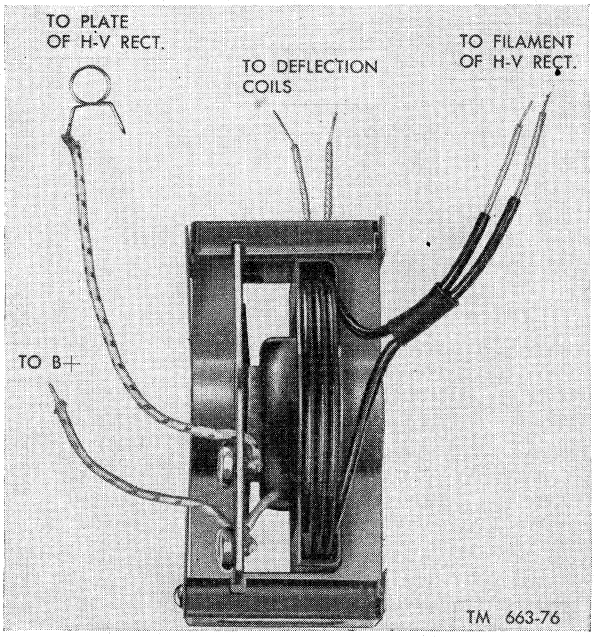


Figure 76. Typical fly-back high-voltage transformer.

lations beyond this point. An example of a typical fly-back transformer is shown in figure 76.

98. High-Voltage Multiplier Circuits

a. When higher voltages than those conveniently obtained from the high-frequency power supplies are required, the increased voltage can be obtained by use of voltage-multiplier circuits. The multiplier circuits for high-frequency power supplies are similar to the voltage multipliers discussed in chapter 2. The operation of high-frequency voltage multipliers is described in terms of the basic circuit in figure 77.

b. The circuit illustrated has a source of d-c voltage, represented by battery E, and a switch which puts capacitor $C1$ across the battery for charging purposes or across the circuit, R and $C2$,

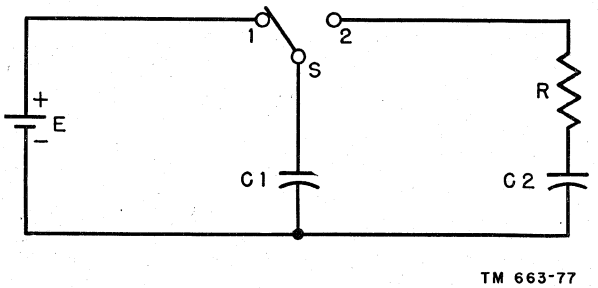


Figure 77. Equivalent circuit for a simple voltage multiplier.

for discharging purposes. At the start of the operation, no charge exists on either of the capacitors. With the switch in position 1, capacitor $C1$ charges up very rapidly to the full voltage of the battery, E. When the switch is turned to position 2, $C1$ discharges into $C2$. Because of the presence of resistor R, a longer time is required to charge $C2$ than $C1$. The function of resistor R is to permit $C2$ to charge during a specific interval of time. While the switch is held in position 2, part of the charge from $C1$ discharges into $C2$. If the two capacitors are equal in value, the voltage across each for equal charges is half the value of E.

c. Consider the following condition: The switch is placed in position 1 for a short time and capacitor $C1$ charges up to the value of E. When the switch is placed in position 2, $C1$ discharges somewhat into $C2$. If this is kept up for a number of times, the voltage across $C2$ becomes greater and greater until eventually both capacitors are charged up to the voltage, E. Actually, the voltage across $C2$ never becomes exactly equal to E because of circuit losses, but for all practical purposes it can be considered equal to E.

d. Figure 78 is a simplified schematic diagram of four stages of voltage multiplication used with a fly-back, high-voltage power supply. The circuit elements in figure 77 correspond to the circuit elements of the first stage of the voltage multiplier in figure 78. Transformer T and the first high-voltage rectifier tube $V1$ in figure 78 are the equivalent of the d-c supply in the basic circuit of figure 77. Capacitor $C1$ corresponds to $C1$ (fig. 77) and the R–C combination of $R1$ and $C2$ corresponds to R and $C2$ (fig. 77). The switch action in the circuit of figure 78 is performed by the positive pulse that is developed in the primary of transformer T during the flyback. Since the time duration of the input sawtooth (when it goes from maximum to minimum in amplitude) is very small, the pulse developed in transformer T is also small in time duration. However, the step-up action of T develops a very high voltage at the output of transformer T.

e. Consider the peak voltage of this pulse as E_m. This voltage is applied to the plate of the first rectifier tube, $V1$. Since the pulse is positive, the rectifier tube conducts and charges $C1$ to the peak voltage E_m with the polarity shown. During the interval following the pulse, $V1$ stops conducting and $C1$ discharges through $R1$ and charges

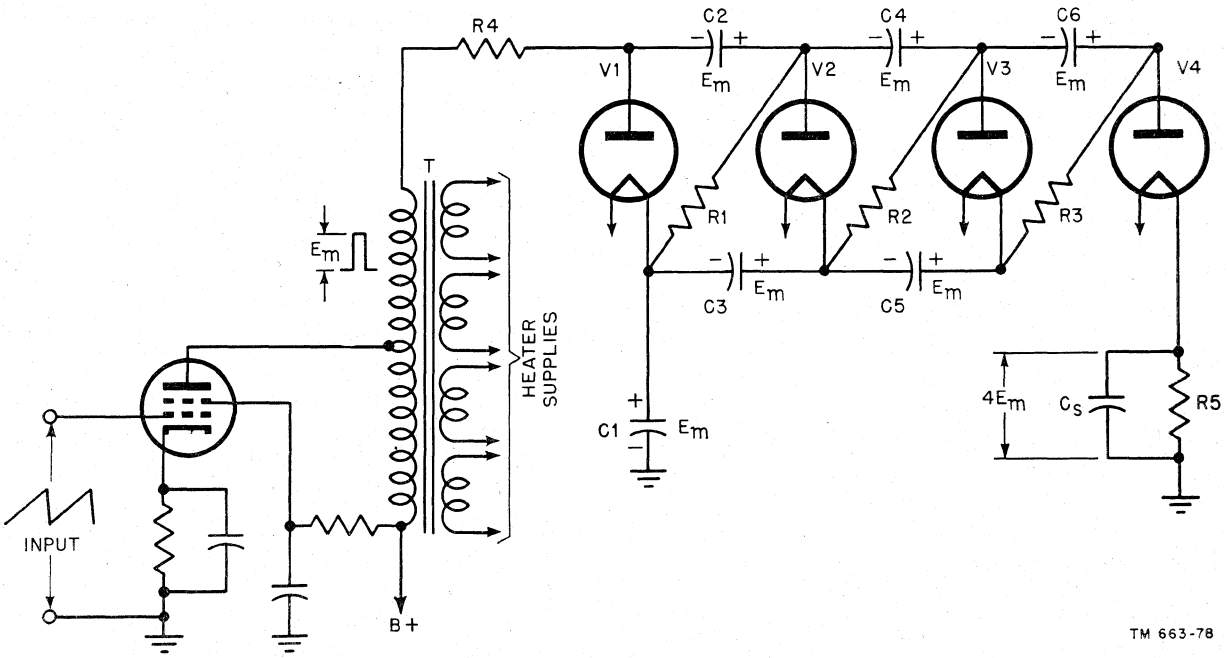


Figure 78. Schematic diagram of high-voltage quadrupler circuit.

$C2$. The discharge path of $C1$ is from ground, B plus, the transformer primary, $R4$, $C2$ (note polarity), and $R1$. The charge on $C2$ reaches the value of E_m after a number of pulses.

f. On the first positive pulse after $C1$ and $C2$ are fully charged, capacitor $C2$ is in series with the positive input pulse and of the proper polarity to add its charge to the pulse so that a total voltage of $2E_m$ is applied to the second rectifier tube, $V2$. This tube conducts and charges $C3$ to voltage E_m. The series combination of $C3$ and $C1$ add to a voltage of $2E_m$. Since their capacitances are equal, each one is charged to a voltage of E_m. The polarity of these voltages is indicated in figure 78. When the positive input pulse has passed, capacitors $C1$ and $C3$ discharge through resistor $R2$ and charge capacitors $C4$ and $C2$. The rest of the discharge path is the same as in the first stage. Capacitors $C4$ and $C2$ now charge up to a total voltage of $2E_m$, but since they are equal in value, the voltage across each one is equal to E_m.

g. On the next positive pulse, $C2$ and $C4$ act in series with the positive pulse, adding their charges to it, and a total voltage of $3E_m$ is applied to the plate of the third rectifier tube $V3$. This tube conducts and charges capacitor $C5$ in a manner similar to that of the second stage. In the interval following the pulse, the three capacitors, $C1$, $C3$, and $C5$, discharge through $R3$ to charge capacitors $C6$, $C4$, and $C2$ to a value of $3E_m$, or a value of E_m across each capacitor. On the next postive pulse, $C2$, $C4$, and $C6$ all act in series with the pulse so that a total voltage of $4E_m$ is applied to the plate of the fourth rectifier tube, $V4$. This tube conducts and produces an output voltage of nearly $4E_m$ across bleeder resistor $R5$ and shunting capacitance C_s. The output voltage is not quite equal to $4E_m$ (about $3.7\ E_m$) because of the voltage drops in the rectifier tubes and the current drawn by the load.

99. Summary

a. R-f and other high-frequency power supplies furnish a convenient method of obtaining high voltages from small, compact power units.

b. In the r-f power supply, voltage generated in a separate oscillator circuit is stepped up to higher values by an autotransformer and rectified to d-c operating voltages by specially designed rectifier tubes.

c. The filaments of r-f rectifier tubes obtain their operating power from a separate winding on the r-f transformer.

d. When the ripple voltage is at a high frequency, it can be filtered easily by small-sized capacitors and resistors.

e. A separate low-voltage power supply is required to provide operating potentials for the

tubes used in r-f power supplies, with the exception of the r-f rectifier tube.

f. One way in which r-f power supplies can be made resonant to different frequencies is by means of a tuning capacitor.

g. The operation of triggered r-f power supplies depends on the application of a pulse.

h. The fly-back power supply is used widely in electromagnetic deflection systems.

i. In the fly-back power supply, a high-voltage positive pulse is developed across a winding on a deflection transformer when a sawtooth waveform is applied to a tube which connects to it.

j. The high voltages developed in r-f power supplies can be increased to very high values by feeding them through voltage-multiplier circuits.

100. Review Questions

a. What is the usual application of an r-f power supply?

b. What three basic types of power supplies fall in the r-f power-supply category?

c. Why is a separate low-voltage power supply required with an r-f power supply?

d. How are the high voltages obtained in an r-f power supply?

e. Why is full-wave rectification not used in r-f power supplies?

f. Why is an r-f power supply so much easier to filter than the low-frequency type?

g. How does the operation of the triggered r-f power supply differ from the conventional power supply?

h. In a triggered or pulsed power supply, during what period does the $V3$ of figure 74 deliver current to the load?

i. How many tubes normally are required in the fly-back power supply?

j. Is $V1$ (fig. 75) cut off during the rise or fall of the applied sawtooth voltage?

k. During what interval of the applied sawtooth is the voltage pulse across T (fig. 75) developed?

l. By what amount does the voltage increase in each stage of the voltage multiplier circuit in figure 78?

m. What is the working voltage of filter capacitor C_S in the voltage multiplier of figure 78 if 5,000 volts is applied to $V1$?

CHAPTER 10

VIBRATOR POWER SUPPLIES

101. General

a. A vibrator power supply converts direct current from a low-voltage power sources, such as a vehicular storage battery, into alternating current that can be rectified and used for the higher d-c potentials required by the operating equipment. When vibrator power supply is used within its rated limits it will furnish the necessary potentials to low-power communications equipment.

b. The difference between a conventional power supply operating from a-c sources (or d-c power lines) and a vibrator power supply is the vibrating mechanism used to convert the low d-c voltages to high a-c voltages, and the special step-up power transformer. The vibrating mechanism is essentially a high-speed reversing switch, which automatically opens and closes sets of contacts by magnetic action when d-c power is applied to it. The vibrator unit is designed to operate at a predetermined frequency, usually between 60 and 250 cps, but for special applications, higher frequencies can be used.

c. The vibrator consists of five basic parts: a heavy frame, an electromagnetic coil and core, a flexible reed or armature, one or more contacts attached to the side of the armature, and one or more semifixed contacts mounted to each side of the armature. In construction, the electromagnetic coil is mounted on one end of the frame, and the armature is fastened rigidly to the opposite end of the frame. The armature contacts and the semifixed contacts are mounted on supporting arms on the sides of the armature. Figure 79 shows a simple vibrator mechanism in which the pole piece is attached to the electro-magnetic coil.

d. During construction, the whole vibrator assembly is sealed in a can and the leads from the contacts are brought out to metal prongs on the base of the can. The vibrator units are plugged into special sockets which are wired permanently

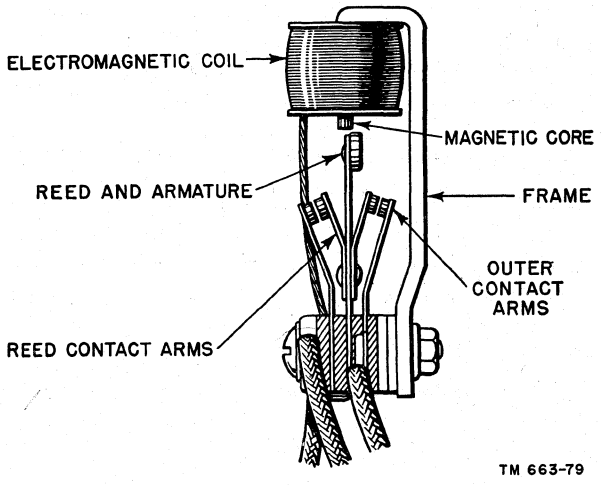


Figure 79. A simple vibrator mechanism.

into the input of the power-supply circuits. This plug-in type of connection insures easy replacement of defective or worn-out vibrators. Since the life of a vibrator often is less than that of an ordinary electron tube, the plug-in method of replacement is convenient and time-saving.

e. The vibrator is connected in the primary of the power transformer between the battery and the primary circuit. When the vibrator is actuated, the battery current through the transformer primary is interrupted at the vibrator frequency rate, resulting in sharp pulses of current through the transformer primary. These pulses of current flow in alternate directions through the transformer primary because of the action of the vibrator contacts which interrupt and reverse the current flow. These interruptions and reversals cause the current to give rise to a changing magnetic field which induces an alternating voltage in the transformer secondary. Because of the step-up ratio of the transformer secondary, the induced a-c voltage in the secondary is many times greater than the primary coltage. This high value of a-c then is rectified, either by a separate rectifier device, or by

additional sets of contacts on the vibrator unit. The rectified voltage then is filtered and regulated in the conventional manner to provide the required value of d-c voltage in the power-supply output.

f. The standard basic structure of two electrical vibrators is described in paragraphs 102 and 103. One of these is the *interrupter*, or the simply constructed nonsynchronous vibrator, which requires the use of some form of rectifying device. The other is the self-rectifying, or synchronous vibrator; as the name implies, it performs the additional function of rectifying the a-c voltage which it produces. The rectified voltage is fed from the output of the vibrator-transformer circuit directly to the filter section of the power supply.

102. Interrupter-Vibrator

a. The circuit of a simple interrupter-vibrator power supply is shown in A, figure 80. With switch *S*1 open, the armature rests midway between the two fixed contact points, 1 and 2, and no contact is made between them. When switch *S*1 is closed, current flows from the negative terminal of the battery through the vibrator coil and to the bottom of the transformer primary at 5. The current continues to flow through the primary winding to the center tap, through the r-f choke *L*1, and back to the positive terminal of the battery. As the current flows through the vibrator coil, a magnetic field is built up which pulls the armature against contact 1. This causes a short circuit across the vibrator coil and deenergizes it. During this time, the pulse of current through the primary, between 4 and 5, is at a maximum, making 5 negative with relation to 4; no current flows through 3 and 4 at this time. The armature, being no longer attracted, springs upward and inertia forces it against the upper contact 2. The current through 5 and 4 of the transformer primary abruptly ceases to flow, but 3 and 4 complete the circuit to the battery. Current now flows from the negative terminal of the battery, through vibrator contact 2, and through 3 and 4 of the primary. It continues through choke *L*1 and flows back to the positive terminal of the battery. During this time, the pulse of current through the primary, between 3 and 4, is at a maximum, making 3 negative with relation to point 4; no current flows through 4 and 5 at this time. The successive closing of contacts 1 and 2 on the vibrator corresponds to one complete cycle of the vibrating frequency and two pulses of current flow in alternate directions through each half of the transformer primary. The magnetic field created by these alternate current pulses induces a voltage in the transformer secondary which has a waveform similar to a square wave (B, fig. 80).

b. As the armature, in A, makes contact with 2, the field of the coil builds up and attracts the armature back to 1. The coil is short-circuited again and the armature springs upward against the top contact, 2, and another cycle is completed. This action continues at a rate dependent on the inherent frequency of the vibrator. Continuous alternating voltages are induced in the transformer secondary and applied to the plates of the full-wave rectifier tube, *V*.

c. Since the making and breaking of the vibrator contacts occur at a comparatively high rate of speed, a small amount of sparking occurs at the contacts. This sparking causes r-f interference and, unless filtered out, it appears in the output of the operating equipment. To minimize this interference, called *vibrator hash*, special r-f filters are used. These filters consist of r-f choke *L*1 and

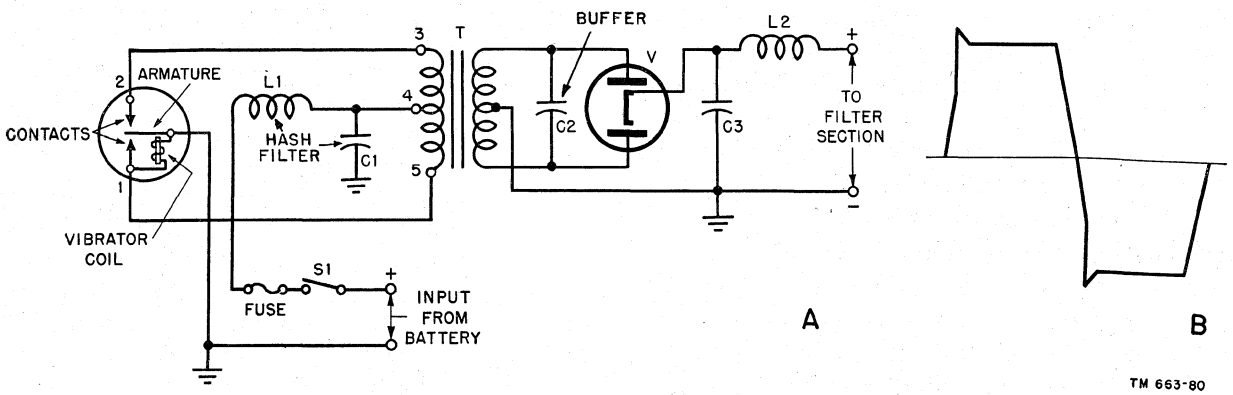


Figure 80. Basic circuit of interrupter vibrator.

capacitor $C1$ in the primary of the transformer and r-f choke $L2$ and capacitor $C3$ in the output of the rectifier tube.

d. Capacitor $C2$ connected across the entire secondary winding is called the buffer capacitor and its exact capacitance is critical. Its function is to absorb the surges that occur when the current is interrupted in the primary. The collapse of the magnetic field is practically instantaneous and causes very high voltages to be induced in the secondary. As a result, if $C2$ is not present excessive sparking occurs at the vibrator contacts which shortens the life of the vibrator. Typical values of capacitors used as buffers are between 0.03 and 0.005 μf. A resistor of approximately 5,000 ohms sometimes is connected in series with the buffer capacitor to limit the secondary current in case the buffer capacitor shorts out. The buffer capacitor should be rated at 1,500 to 2,000 working volts in power supplies delivering voltages of 250 volts or higher.

103. Self-Rectifying Vibrator

a. Figure 81 shows the circuit of a self-rectifying or synchronous vibrator power supply. A rectifier tube is not used in this circuit and rectification is accomplished by means of an extra set of contacts, 3 and 4, on the vibrator. These contacts are connected to points A and C on the transformer secondary. A positive rectified d-c voltage is obtained from center tap B on the secondary winding.

b. When $S1$ is closed, the action of the primary of T and contacts 1 and 2 are identical with that of the interrupter vibrator previously described. A different condition exists in the secondary circuit because of the presence of additional contacts 3 and 4 on the vibrator. A pulsating d-c similar to that obtained from any rectifier exists between point B of the secondary winding and ground. This rectified output is fed to a filter section and appears as the required value of d-c voltage in the output. This action takes place as follows:

c. Ground or B-minus is the lowest point of potential for the circuit, and all other points are positive with relation to ground. When the vibrator coil is energized and the armature is pulled against contact 1, contact 3 also is closed by the armature. This places C, on the bottom of the secondary winding, at ground potential since the armature is grounded and it becomes the common B minus for the power supply momentarily. The center tap, B on the secondary winding, is positive with relation to C and the voltage across the output terminals is positive in polarity. When the vibrator coil is de-energized, the armature springs against contacts 2 and 4. A on the transformer secondary then is placed at ground potential and becomes B minus. Since B still is positive with relation to A, and the voltage existing across the output terminals has the same positive polarity as before. Since the pulsating current through the power supply always flows in the same direction, the current at B is the same as that obtained from a full-wave rectifier. The reversal of the B-minus point from A to C and then from C to A on the transformer secondary occurs at such a rapid rate that the output of the power supply is a pulsating d-c voltage. (If the battery polarity is reversed, the synchronous vibrator will not have the output voltage shown unless the transformer

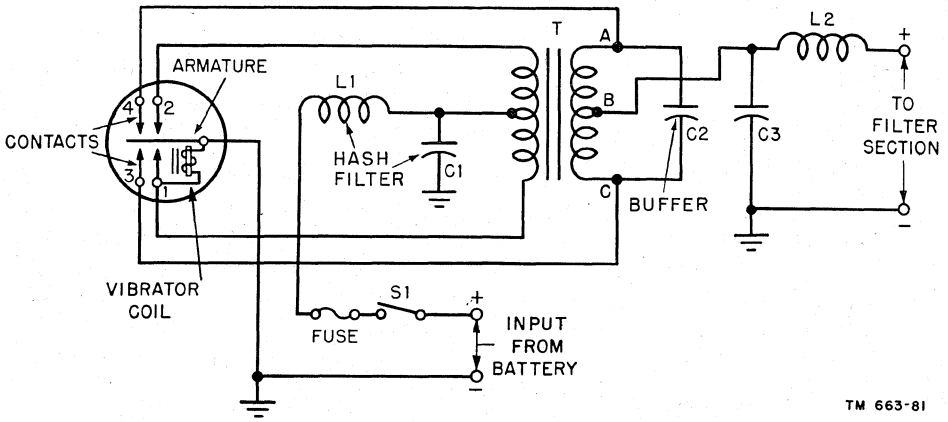


Figure 81. Circuit of self-rectifying vibrator.

primary or secondary connections also are reversed.)

d. R-f chokes $L1$ and $L2$ and capacitors $C1$ and $C3$ in the primary and secondary circuits of the transformer are filtering networks to filter out the vibrator hash. To help eliminate r-f interference, center-tapped resistors sometimes are connected across the transformer primary, or a capacitor is connected across the entire primary winding. The power supply should be well shielded to prevent radiation of the r-f interference caused by sparking at the vibrator contacts.

104. Application

a. Vibrator power supplies are designed and constructed to meet specific requirements. In military applications, vehicular storage batteries having voltage values of 6, 12, or 24 volts are used to operate this type of supply. This is accomplished by using a power transformer having a number of taps on its primary winding to accommodate the different battery voltages. Since the primary winding always is tapped in the center, the additional taps must be placed in pairs at corresponding points on the two halves of the winding. Two switches are ganged together to transfer simultaneously the two corresponding taps on the two sections of the primary winding; this adjusts the primary to the particular battery voltage being applied to the power supply.

b. Combination vibrator power supplies are constructed to operate on both an a-c and a battery power source as required. Use of a power transformer having an additional primary winding for use with a-c voltages is one method of accomplishing this. The primary winding used for the vibrator is tapped and can be used as the source of filament power when operating on a-c. This circuit requires a separate rectifying device, since the same high-voltage secondary is used for both a-c and d-c operation.

c. Another combination power-supply design uses two separate power transformers, with independent rectifiers, in the vibrator or the a-c input circuit. These two independent input circuits are connected in parallel across a common filter circuit. Either of the two input circuits can be selected at will by connecting the proper source of power and closing the switch.

d. The use of selenium rectifiers simplifies the design of this combination power supply since no filament power is required. An input circuit consisting of an interrupter vibrator and its associated power transformer is used for d-c operation, the stepped-up voltage on the transformer secondary being rectified by the selenium rectifier(s). A-c input voltage is applied through a switch directly to the selenium rectifiers and in shunt with the transformer secondary winding. The voltage induced in a tapped section of the vibrator transformer primary provides filament power for the tubes in the operating equipment being supplied.

e. Although there are still a number of circuit arrangements for providing combined operation from both a-c and d-c input sources, the examples given here will suffice for general purposes. Other forms of combination vibrator power supplies include circuits operating from the same input source, but providing two or more entirely different power-supply output voltages to operate different equipments. By proper circuit arrangement, the outputs of these combined supplies can be either positive or negative, or both, and of varying values of output voltages.

f. Any of the conventional rectifier circuits, such as half-wave, full-wave, bridge rectification, and voltage multiplication, can be used in vibrator power supplies. Other power-supply features, such as voltage regulation and voltage division, are equally applicable to this circuit. Vibrator power supplies are used widely in transportable communications equipment and in mobile installations.

105. Summary

a. Vibrator power supplies convert direct current, from a d-c prime power source, to alternating current which can be used to furnish operating potentials for low-power equipment.

b. The vibrator consists of a magnetically actuated vibrating mechanism which causes the d-c input current to flow in pulses through alternate halves of a special power transformer.

c. The rising and falling magnetic field caused by the current pulses in the transformer primary induces an alternating square wave in the secondary.

d. Two basic vibrators are used widely—one the nonsynchronous, interrupter vibrator, the other the synchronous, self-rectifying vibrator.

e. A separate rectifier is required with the nonsynchronous vibrator.

f. Rectification is accomplished with the synchronous vibrator by connecting an added pair of contacts to each end of the secondary winding. The voltage obtained from the center tap on the secondary winding then is always positive with relation to ground.

g. The frequency range of the vibrating mechanism is approximately 115 to 250 cps.

h. The purpose of the buffer capacitor is to absorb the high-current surges occurring in the secondary. Its value is critical.

i. Several types of vibrator power supply operate from both low-voltage d-c sources and standard a-c sources simply by throwing a switch to the required input circuit.

j. Vibrator power supplies find widest application in mobile and transportable equipment.

106. Review Questions

a. What is the purpose of a vibrator power supply?

b. What are the five basic parts of the vibrating mechanism?

c. Where is the vibrator connected in the power-supply circuit?

d. What are the two basic types of vibrators?

e. How is rectification obtained in the synchronous vibrator?

f. What kind of voltage waveform does the vibrator produce in the secondary of the power transformer?

g. What is vibrator hash?

h. How is it minimized?

i. What is the purpose of the buffer capacitor?

j. Where is the vibrator power supply used most widely?

CHAPTER 11

DYNAMOTORS, ROTARY CONVERTORS, INVERTERS

107. Dynamotors

a. A dynamotor (fig. 82) is a device commonly used for transforming a d-c voltage to a higher or lower d-c voltage. The transformation is accomplished by using a d-c motor to drive a d-c generator. The input to the motor is taken from a d-c prime power source. The output from the generator is the d-c voltage required. In the dynamotor, the motor and the generator are combined on a single frame. The rotor winding of both the motor and the generator is wound on a single armature. Although they have separate commutators, they have the same stator field winding.

b. The rotor winding of the d-c motor is called the motor winding. The input from the prime power source is applied to the rotor winding and the stator field winding. These two windings are arranged so that their magnetic fields oppose, causing the armature to rotate. In the schematic diagram of the dynamotor (fig. 83) the d-c motor consists of the field winding, the motor winding, and the motor commutator, at which the input is applied. Because the field winding is in parallel with the motor winding, this is known as a shunt-wound motor. A π filter in the input removes variations in the d-c voltage caused by sparking and other disturbances at the motor commutator. It also reduces interference to other equipment which may be connected to the same power source.

c. The d-c motor drives a d-c generator, which delivers the characteristic output of the dynamotor. The generator consists of a rotor field wound on the same armature as the rotor field winding of the motor, the same stator field winding as the motor, and a separate generator commutator at the end of the armature opposite the motor commutator. A π filter at the output serves to remove the effects of hash and sparking. The d-c output of the dynamotor is taken from this filter.

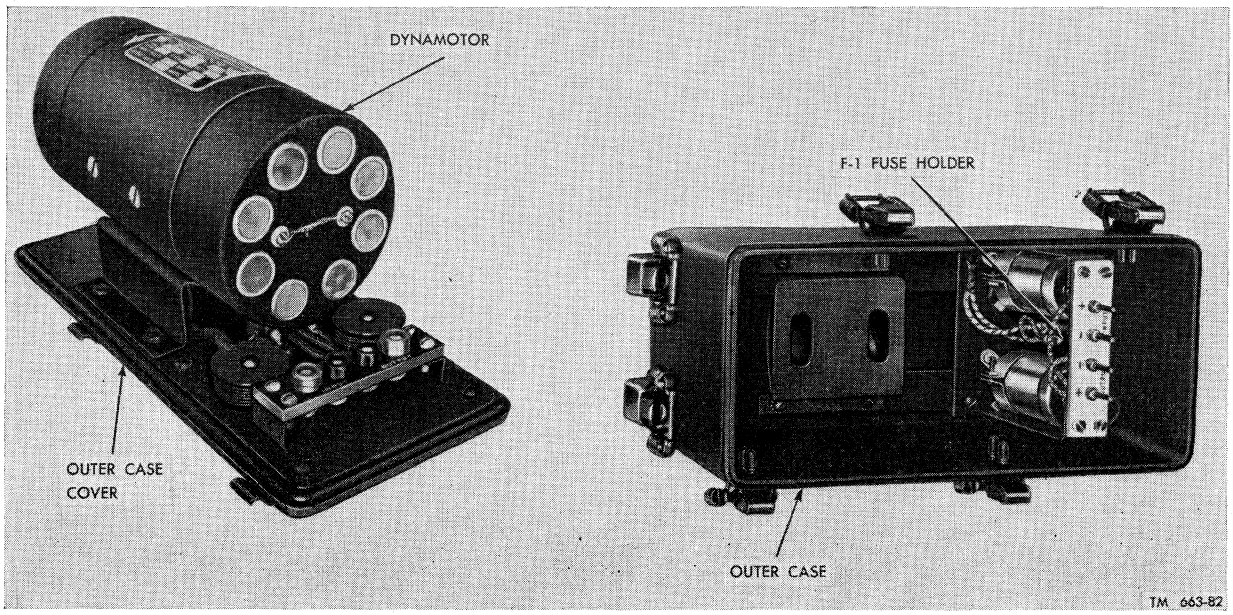


Figure 82. Step-down dynamotor.

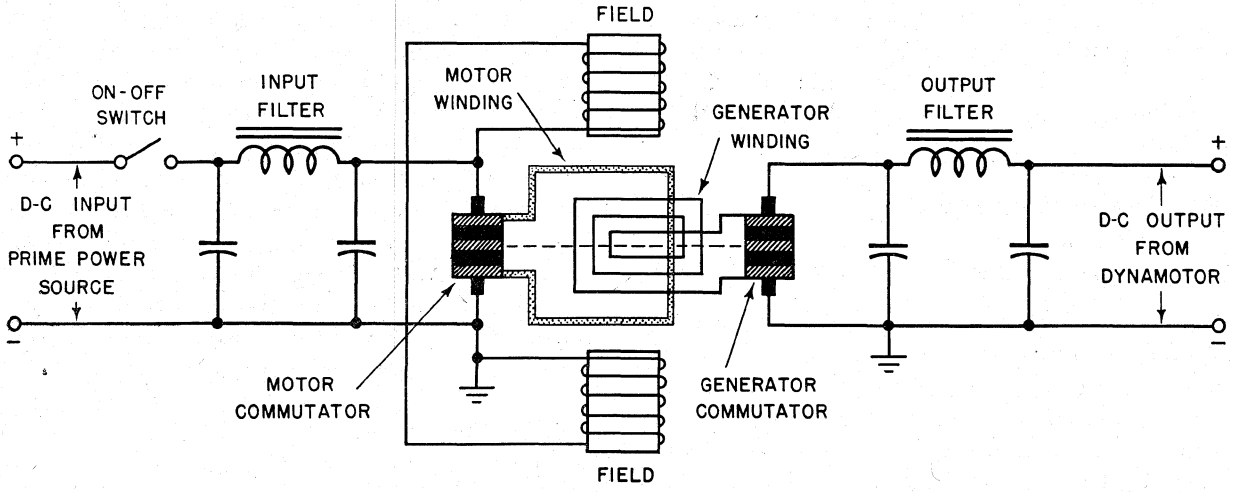


Figure 83. Simplified diagram of step-up dynamotor.

d. When the on-off switch is turned on, the d-c voltage is applied to the motor commutator, energizing the field and motor windings. The opposing magnetic fields of these two windings cause the armature to rotate. Because the generator winding is fixed to the armature, it rotates also. The relation between the motor and the generator is purely mechanical. *There is no electrical connection between the motor and the generator rotor winding.* This arrangement serves to isolate the equipment being supplied from the prime power source. When the generator rotor winding is rotated by the motor, it cuts the magnetic field about the stator winding. This action induces a voltage in the generator winding.

e. Because the motor and the generator use the same field winding, the relation of the input voltage to the output voltage depends on the ratio of the number of turns in the generator rotor winding to the number of turns in the motor winding. Changing the number of turns in the motor winding will change the speed of the motor and change the output voltage. Increasing or decreasing the number of turns on the generator rotor winding also will change the output voltage.

f. Excessive sparking at the commutator is an indication of worn-out brushes or commutator trouble. Trouble in the commutator usually is the result of a *high mica* condition where the copper commutator segments have worn down below the strips of mica which separate and insulate them. This is corrected by undercutting the mica strips until the level of the mica is below the surface of the copper segments.

g. Dynamotors operating from storage batteries ranging from 6 to 32 volts can deliver 1,000 volts or more at various current drains. One disadvantage of a dynamotor is that the output voltage cannot be adjusted to different values without changing the excitation of the motor winding. however, when required, this can be accomplished by inserting a variable resistance or a booster circuit (auxiliary field system) in the primary or secondary circuit.

h. For successful dynamotor operation, the following factors are very important: The connecting leads to the machine must be short and heavy. The dynamotor should be mounted on some form of rubber support to reduce mechanical vibration. All of the filter capacitors should be grounded at a common point on the dynamotor frame, preferably at a point close to the commutator brush holders. In order to prevent interfering r-f radiations, the entire unit may require shielding or removal to a distance several feet from the operating equipment being supplied with power.

i. The major difference between dynamotors for various applications, is in the input and the output arrangement. A machine designed to convert an alternating current of one value to an alternating current of a different value has slip rings on both the motor side and the generator side of the unit. This dynamotor is used rarely, since the step-up or step-down of the alternating voltage can be accomplished conveniently by means of a transformer. A dynamotor designed to convert direct current to alternating current has a commutator on the motor end and slip rings on the generator

end of the machine. As mentioned in *c* above, a dynamotor used to convert a direct current of one value to a direct current of the same or different values has a commutator on both the rotor and the generator ends.

108. Rotary Converters
(fig. 84)

a. By definition, a rotary converter is a machine that changes electrical energy of one form to electrical energy of another form. The rotary converter can convert alternating current to direct current, or direct current to alternating current. It can be used also to change frequency and phase. When used to convert direct current to alternating current, it is known as an *inverted converter*, or simply an *inverter* (par. 109). Both types of machine are used in military applications, but the inverter is used most widely. The rotary converter, or *synchronous converter*, is constructed with slip rings at one end for alternating current, and a commutator at the other end for direct current. For special applications the rotating armature can be driven by a separate motor, and both alternating and direct current can be obtained simultaneously from the slip rings and commutator.

b. The rotary converter has a single armature winding operating in a single field. This single armature winding serves a dual function as motor and generator. It is connected to the slip rings on the a-c side and to the commutator on the d-c side of the machine. Rotary converters can be designed for operation on either single-phase or polyphase input. When they have a single armature winding, no step-up or step-down in the applied input voltage can be accomplished within the converter. The output equals the input, minus the losses in the converter. Therefore, when different voltage ratios are required, external means must be used to accomplish the required results. In rotary converters designed with separate input and output windings on the armature, various ratios of input and output can be established, depending on the number of turns in each winding.

c. The a-c input is applied to the armature winding through brushes and slip rings. The d-c output voltage is taken off the armature through brushes and a commutator (not shown in the illustration). The field windings are connected in shunt with the d-c output voltage. To start the armature rotation, a special winding, called a damper, is mounted on the field-pole faces. When a-c voltage is applied, current flows through the armature winding, and a magnetic field is set up around the armature. This field creates an opposing magnetic field in the damper windings which opposes the armature field, and the armature turns. The converter rapidly approaches a synchronous speed while operating as an induction motor. At this point the converter is made to *lock in* as a synchronous motor by the generated d-c exciter voltage applied across the field coils. The principle of the synchronous motor is that it maintains a constant speed at all normal loads when supplied with an input voltage of a definite frequency. Consequently, a 115-volt, 60-cps syn-

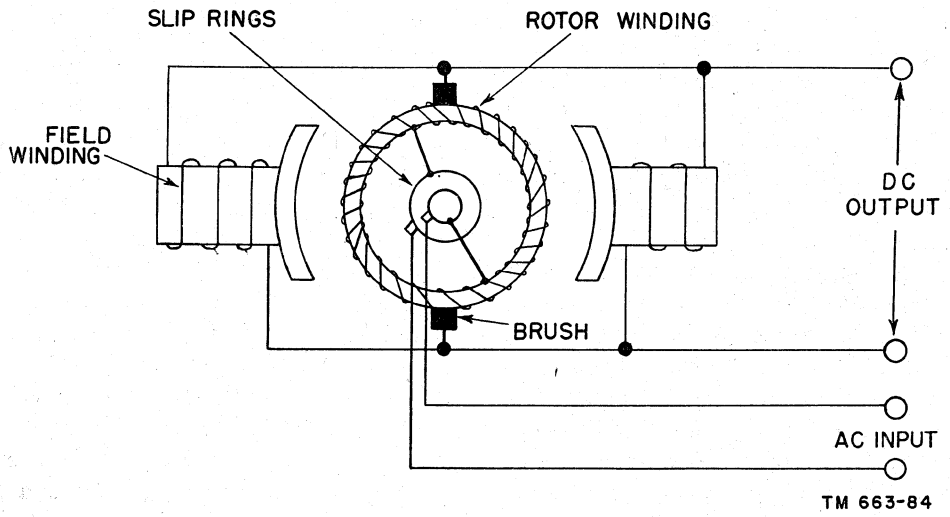


Figure 84. Simplified diagram of rotary converter.

chronous motor designed to operate at, say, 800 rpm will maintain this constant speed, or *lock in*, once this speed is attained for as long as the rated voltage and frequency are applied, regardless of wide load changes.

d. The damper-winding starting arrangement described applies to small, low-power rotary converters. For starting high-power units, a separate starting motor can be used. When starting voltage is applied to the slip rings, it usually is of low value and the converter gradually is brought up to the operating speed. This is necessary because high a-c voltages are induced in the field windings, causing a strain on the insulation. The d-c voltage taken off the secondary has a value equal to the peak value of the applied a-c voltage minus the losses in the machine. Therefore, where different voltage values are required, transformers must be used ahead of the converter to raise or lower the input voltage. The dc obtained in the output requires filtering to remove the commutator ripple and the r-f hash created by sparking at the brushes. To prevent excessive sparking at the brushes during the starting period, some converters are equipped with special brush-lifting levers which lift the brushes off the commutator until the synchronous speed is attained.

e. If the applied a-c voltage falls below the operating value because of a short circuit or a disturbance in the line, the converter can drop out of synchronism and stall under load. Also, if the excitation voltage on the field winding is decreased for any reason, the speed of the converter can increase to the danger point. The converter can be started as a shunt motor from the d-c side and synchronizing operating voltage can be applied to the a-c side after it has reached synchronous speed. Converters are started more easily if the load is removed during the starting period. Sometimes, when the converter locks in at the synchronous speed, the polarity of the d-c voltage on the output terminals is reversed. Usually, a switch is provided to change the polarity of the output voltage to that required.

109. Inverters

(fig. 85)

a. When a rotary converter is reversed (operating with direct-current input and alternating-current output), it is called an *inverted converter*, or simply an *inverter*. The inverter is used widely in military applications to convert the d-c voltage from a vehicular storage battery to alternating voltage for application to power-supply input. When the operating switch is closed, current flows through the relay coil and a magnetic field is created which attracts the relay plunger, and so closes the relay contacts in the input line. The contacts remain closed as long as current flows through the relay coil. The input line to the relay contacts is fused; this prevents excessive current drain which may be caused by an abnormal condition in the inverter. The filter unit in the input to the inverter reduces the r-f hash generated at the brushes and commutator of the motor armature.

b. The inverter shown in the diagram of figure 85 has two armatures and two fields functioning separately as a motor and a generator. The reason for this arrangement is that the inverter is unstable if the same armature and field are used for both a-c and d-c. Maximum possible stability is one of the requirements in military applications, and this machine is used widely with communications equipment. As an additional assurance of stable operation, the field of the motor section is compounded, consisting of both a series and a shunt winding. This provides better speed regulation under varying load and a reasonably constant frequency in the a-c output.

c. Generator output can be obtained in two ways. In the first method, the generator has a stationary field winding to which the exciter voltage is applied and a rotating armature from which the voltage is taken. In the second method, the field winding is constructed on the armature and the exciter voltage is applied through brushes, commutators, or slip rings.

d. Application of exciter voltage to the field causes the field to generate a voltage in the stator winding (fig. 85). The generated voltage then is removed by means of terminals connected directly to the stator. The d-c field rotor is ganged mechanically to the motor armature and rotates with the speed of the motor. The exciter voltage is applied to the rotating field through brushes and a commutator. To insure an unvarying field voltage the exciter voltage is regulated before application to the field. The flow of current through the d-c field winding creates a magnetic field which is rotating at the speed of the motor.

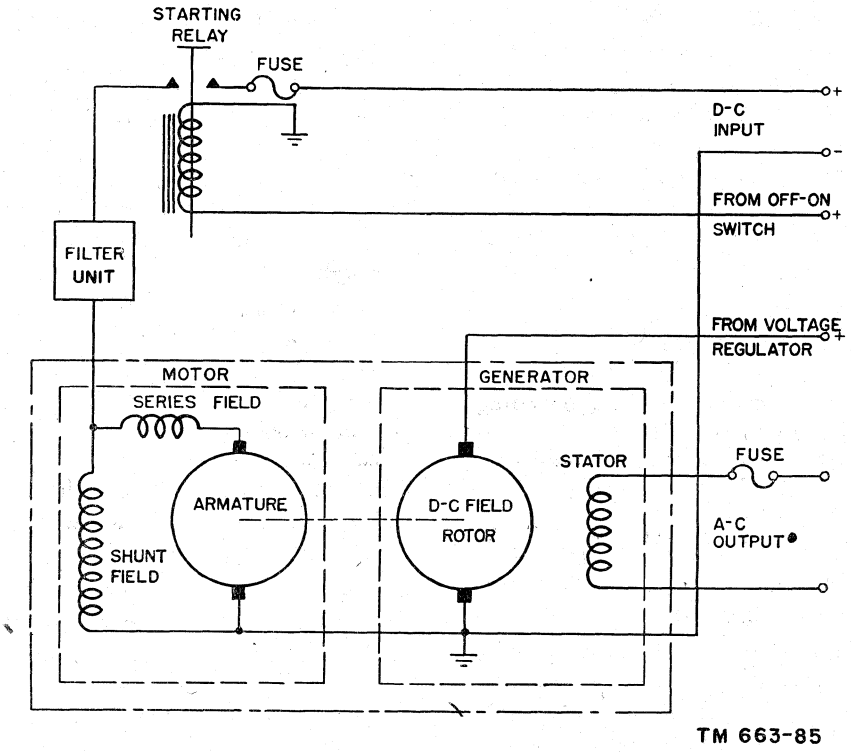


Figure 85. Circuit diagram of an inverter with two independent armature and field windings.

The rapidly moving lines of force cut the stationary winding and a voltage is induced in the stator. The output from the stator is an a-c voltage of the value, phase, and frequency determined by the design and power rating of the particular inverter unit. The output winding is fused to prevent damage to the inverter from excessive current drains by the operating equipment.

e. If the inverter has a single armature winding, connection to an inductive load tends to weaken the inverter field. This causes the machine to speed up, changing the frequency; the output voltage is not changed greatly. This instability in the speed of an inverter with a single armature winding is inherent in the machine unless the inverter field is excited by a special exciter circuit directly connected to the inverter output. Any tendency toward increase of speed is corrected by a corresponding increase in exciter voltage, causing a stronger field. Other methods of speed control include the use of a centrifugal overspeed device that automatically opens the line connections if the inverter speed increases beyond a predetermined operating point. The use of dual windings on the armature helps to correct for excessive speed (fig. 85).

110. Summary

a. Dynamotors, rotary converters, and inverters are electromechanical devices used to change the form and value of voltages applied to them.

b. The common use of the dynamotor is to convert one value of d-c voltage to a higher or lower value of d-c voltage.

c. A dynamotor consists of two windings on the same armature operating with a single field winding. The input winding on the armature serves as the motor winding, the output winding as the generator winding.

d. A rotary converter is used to convert alternating current to direct current. It has a single armature winding and a single field winding performing the functions of motor and generator.

e. When a rotary converter is used to convert direct current to alternating current it is called an inverted converter, or an inverter.

f. Both direct current and alternating current can be obtained from a single rotary converter by driving its armature with a separate motor. An a-c voltage is taken from the slip rings, and a d-c voltage is taken from the commutator.

g. Rotary converters and inverters can be designed for single-phase or polyphase operation.

h. Rotary converters also are called synchronous converters because they are designed to lock in at a predetermined speed when connected to the proper source of voltage and frequency. When starting, the motor operates as an induction motor until the synchronous speed is reached. Then it operates as a synchronous motor.

i. Inverters find wide military application in converting the d-c voltage of a storage battery to the a-c voltage needed for power supplies and other devices.

j. For increased stability, the inverters used in military applications have two armature windings, one for the motor and the other for the generator.

111. Review Questions

a. What is the purpose of a typical dynamotor?

b. Why are two windings used on the armature of a dynamotor?

c. How are different voltage ratios obtained by means of the dynamotor?

d. What is the purpose of a rotary converter?

e. How does the function of the inverter differ from that of the rotary converter?

f. What is the usual military application for the inverter?

g. Why do some inverters have two independent armature and field windings?

h. Why do electromechanical devices like these incorporate filter circuits?

i. Why is the converter (or inverter) called synchronous?

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